6 Great Astronomers

BY J. G. CROWTHER

TYCHO BRAHE · KEPLER · HALLEY

HERSCHEL · RUSSELL · EDDINGTON

SIX GREAT ASTRONOMERS

In the same series

SIX GREAT ACTORS	Richard Findlater
SIX GREAT AMERICANS	Kenneth M. King
SIX GREAT ARCHAEOLOGISTS	Frances Wilkins
SIX GREAT ARCHITECTS	Robert Lutyens
SIX GREAT AVIATORS	John Pudney
SIX GREAT CHRISTIANS	Peggy Chambers
SIX GREAT COMPOSERS	John Warrack
SIX GREAT DANCERS	Mary Clarke
SIX GREAT DIARISTS	Kay Dick
SIX GREAT DOCTORS	J. G. Crowther
SIX GREAT ENGINEERS	J. G. Crowther
SIX GREAT ENGLISHMEN	Aubrey de Sélincourt
SIX GREAT ENGLISHWOMEN	Yvonne ffrench
SIX GREAT EXPLORERS	David Divine
SIX GREAT INVENTORS	J. G. Crowther
SIX GREAT MISSIONARIES	Phyllis Garlick
SIX GREAT MOUNTAINEERS	Ronald W. Clark
SIX GREAT NATURALISTS	R. S. R. Fitter
SIX GREAT NOVELISTS	Walter Allen
SIX GREAT PAINTERS	Michael Levey
SIX GREAT PLAYWRIGHTS	Aubrey de Sélincourt
SIX GREAT POETS	Aubrey de Sélincourt
SIX GREAT RAILWAYMEN	Richard Hough
SIX GREAT SAILORS	David Divine
SIX GREAT SCIENTISTS	J. G. Crowther
SIX GREAT THINKERS	Aubrey de Sélincourt
SIX GREAT TRAVELLERS	John Lennox Cook

SIX GREAT ASTRONOMERS

TYCHO BRAHE KEPLER HALLEY
HERSCHEL RUSSELL EDDINGTON

by

J. G. CROWTHER

'Through knowledge we behold the world's creation'

EDMUND SPENSER

HAMISH HAMILTON
LONDON

First published in Great Britain 1921
by Hamish Hamilton Ltd
90 *Great Russell Street London WC*1

PRINTED IN GREAT BRITAIN
BY EBENEZER BAYLIS AND SON, LTD
THE TRINITY PRESS, WORCESTER, AND LONDON

CONTENTS

ILLUSTRATIONS

ACKNOWLEDGMENTS

The main sources of information have been given at the end of each chapter. The author acknowledges with gratitude his indebtedness to the authors of these works.

He is particularly indebted to Mrs. Frank K. Edmondson for reading the chapter on her father, Henry Norris Russell, and sending his portrait.

He also acknowledges permission from the following to reproduce illustrations: The Royal Society for the portrait of Edmond Halley by Thomas Murray; W. Kohlhammer GmbH of Stuttgart and the Séminaire Protestant of Strasbourg for the portrait of Johannes Kepler; Pix Inc. of New York for the portrait by George Karger of Henry Norris Russell.

INTRODUCTION

ASTRONOMY arose out of prehistoric man's attempts to secure control over his environment, particularly to gain food and health, and find his way across the wildernesses of land and water. He supposed that because he could act according to his own will, and to some extent make things go as he wished, all the happenings in nature must be due to the wills of living beings.

The most important living things he could think of when he was a primitive hunter were animals such as the bull, lion and fish. After he had domesticated animals and invented agriculture, he came to regard the ram as very important. He adopted all these animals as totems or gods of his tribes. He supposed that because of their importance in his life they must have special powers of influencing nature and the course of events.

As man developed, he made his notions of these animal-gods more general. He convinced himself that they lived in the sky, and controlled everything that happened on the earth. He thought of the stars as ornaments or jewels worn by these gods, and he began to call the group of stars worn by a particular animal-god by the name of that god. In this way, the main groups or constellations of stars received their names. It was consideration of the gods which came first, not the stars.

The groups were gradually modified to form twelve

main constellations, the sun appearing in the place in the sky occupied by each of these according to the twelve months of the year, that is, the twelve periods from new moon to new moon that occur within one year.

The names of the constellations: the Ram, Bull, Heavenly Twins, Crab, Lion, Virgin, Balance, Scorpion, Archer, Sea-goat, Water-carrier and Fish reflect their ancient and primitive origin. Insight into the actual age of some of these names is derived from the very remarkable discovery of the Greeks, that the place of the sun in the sky when day and night are exactly equal does not remain constant, but changes slowly with the centuries.

The poet Aratus in the third century B.C. referred to an irregularity in the axis of the heavens. Then, about a hundred years later Hipparchus, the greatest astronomer of the ancient world, showed that the place of the sun in the constellations when day and night are equal, that is, at the equinoxes, would make a complete circle of the heavens in about 25,000 years. His result is substantially correct. His achievement in working it out, with the information at his disposal in 150 B.C., is one of the greatest in astronomy, and indeed in the whole of human intellectual endeavour.

The explanation of this phenomenon was given nearly two thousand years later by the incomparable Isaac Newton, who showed by his theory of mechanics that the spinning earth behaved like a top, whose axis completed one whole wobble in about 25,000 years.

Prehistoric man counted the New Year from the

date when the length of the day began to exceed the night: the vernal equinox. In Greek times, this occurred when the sun was in the constellation of the Ram. Today it takes place when the sun is in the Fish. The Mesopotamians started their list of constellations with the Bull, which suggests that they may have settled the description of this constellation and its name at a time when the vernal equinox was marked by the entry of the sun into it. If this is so, then it can be calculated from the rate of the precession of the equinoxes that this must have been in about 2450 B.C.

The name of the constellation of the Water-carrier is the only one of Egyptian origin; the symbol for it is the Egyptian hieroglyph for water. If the Egyptians named this constellation when the sun's entry into it marked the beginning of the Nile floods, then it can be calculated that the name is 15,000 years old.

Prehistoric man's equipment for securing the necessities of life was very inadequate. He kept up his courage in the face of famine, disease and disaster by believing that he had more power over things than he actually had. He convinced himself that he could control nature and his enemies by operations which are now described as magic. This very human thing is a product of wishful thinking, and it almost completely enveloped every activity of primitive man. It consisted in its early stages of a great deal of hope mixed up with a little fact. As man progressed, the proportion of fact gradually increased; as the knowledge of fact became more complicated, men began to call it science.

That part of magic concerned with the stars is called

astrology, and astronomy may be regarded as the fact and science which has gradually grown out of astrology.

The first studies of the stars arose from magical and astrological motives. The immensely detailed observations of the stars by the Mesopotamians, which led to the discovery of many important astronomical facts, was inspired by astrological motives. They believed that if they accumulated very detailed observations of the stars they would be able to forecast the events of life, business and politics in the immediate future, and gain the power of influencing them.

The separation of the facts about the stars from what men have wished to believe about them has been a very slow process. The Greeks were the first to make a definite separation, and are therefore the founders of the science of astronomy. But they managed to keep fact and belief apart for only a century or two, before the wish to believe again became dominant. Even up to the time of Kepler, fifteen hundred years later, astronomy remained entangled in astrology. In Kepler's day, astrology was still seriously studied in the universities. Today, astrology has been expelled from the universities, but it is far from dead. It provides an important feature in many newspapers, and broadcasts on it are given through those miracles of modern scientific achievement: radio and television.

The separation of science from magic, of astronomy from astrology, has been connected with advances in technology. When men really succeed in doing things they become more detached in their wishes and beliefs.

The astronomical content in primitive magic and as-

trology was increased enormously by the invention of agriculture, probably about 10,000 years ago. This provided a more secure and settled life, which enabled men to take a more dispassionate view of things, and it increased the need for the exact study of particular phenomena of fundamental importance to agriculture, such as the dates of the seasons, the times for sowing and the mating of animals.

The next great advances in the separation of astronomy out of astrology have arisen from the needs of navigation. The stars are the only guide across the waters, out of the sight of land. They have in consequence been studied with a peculiar intensity by maritime peoples. The night sky over the ocean is far more abstract than over the land. The infinite variety of undulations, fields and buildings is gone, and the observer is presented with what is virtually a mathematical diagram. There is the more or less plane surface of the sea, and the dome of the sky studded with points of light.

It is not surprising that the Greeks, who lived in the islands of the Eastern Mediterranean, and whose life was based on navigation, should have studied this abstract picture of the night-sky over the sea with particular attention. They became the inventors of abstract thought. After a short period of brilliant achievement they were submerged by the Romans, who were agriculturists and less emancipated. Under their influence the ancient magic and astrology became dominant again, and astronomy did not revive until the new maritime nations arose, and, in particular, discovered America. It was this which broke the Roman agriculturist view of the

earth as a flat estate, and indicated that it was indeed a globe spinning in space. The effort of mind required to navigate the stormy Atlantic Ocean was greater than that needed to voyage from one Greek island to another. It stimulated the measurement and interpretation of the movements of the stars which culminated in the achievements of Newton.

The early Greek astronomers appear to have been the first to escape from the idea that the earth is fixed. The Pythagorean Philolaus suggested that the earth revolved around a central fire (which was not the sun). Heraclides of Pontus, one of Plato's pupils, believed that the daily revolution of the stars was apparent, and was due to the rotation of the earth on its axis.

Aristarchus of Samos, who flourished at Alexandria about 280 B.C., suggested that the earth, besides rotating on its axis, also revolved round the sun, which was fixed. He explained the seasons by the inclination of the earth's axis. He appreciated that the stars were very distant, and that the sun was a star. A successor of his at Alexandria, Eratosthenes, who flourished about fifty years later, was the first to calculate the size of the earth. He deduced it by measuring the angle of the sun from the zenith at Alexandria, when the sun was known to be directly overhead at the same moment at the distant place of Syene in Upper Egypt. The angle is approximately the same as that which the distance between Syene and Alexandria makes with the centre of the earth, and from this the radius of the earth is easily calculated. His result appears to have been approximately correct.

Greek astronomy was raised to its highest achievement by Hipparchus, who flourished from 161 to 126 B.C. He had an observatory on the island of Rhodes, and unlike *most of the Greeks, who preferred to speculate and calculate about data collected by the Mesopotamians* and Egyptians, paid as much attention to observations as to mathematical theory. He observed the position of more than a thousand stars, and made the most important star-catalogue of the ancient world. Besides this, he made three other major contributions. He compared recent observations with ancient ones in a scientific manner, so that it became possible to discover changes which were too slow to be detected within one lifetime. In this way, from the data in his star-catalogue, he made his wonderful discovery of the precession of the equinoxes.

To these achievements, he added two others as great, but very different in nature. He virtually invented the science of trigonometry, which facilitates the kind of calculations of the geometry of figures on a plane, and on the surface of a sphere, which are particularly required in astronomy.

Then he worked out the movements of the sun and moon as a mechanical system. The Greek mathematicians Eudoxus and Apollonius had suggested that the movements of the heavenly bodies could be described by a combination of circular motions. With the aid of eccentrics, or movements in circles which are off centre, and epicycles, in which a body revolves round a centre which is at the same time rolling along the circumference of a circle around a second centre, Hipparchus succeeded

in giving a tolerable description of the motions of the sun and moon.

He found the data on the movements of the planets not sufficiently accurate to give a significant result, so he started making exact observations of them, with the conscious intention of leaving to his successors new data which would be sufficiently accurate to enable them to solve the problem; showing in this the advanced maturity of his scientific outlook.

From the improvements he made in the description of the motions of the sun and moon, Hipparchus succeeded in greatly improving the accuracy of the forecasting of eclipses.

Hipparchus's trust in future astronomers was not misplaced. Three hundred years later, about A.D. 150, his famous successor Claudius Ptolemy, the last of the great Greek astronomers, appeared. Ptolemy systematized and perfected Hipparchus's work, incorporated much from the earlier Greek astronomers, and contributed substantial new work of his own. He described all this in his masterpiece which became known by the Arabic name *Almagest*, which is derived from the Greek word for 'greatest'. The most noteworthy part of Ptolemy's own contribution, accomplished with great skill and labour, was a theory of the motions of the planets, which enabled them to be calculated with reasonable accuracy.

The system of Hipparchus and Ptolemy was based on the assumption that the earth is fixed and the heavenly bodies revolve round it. Hipparchus probably well knew that from the mathematical point of view the movements

of the heavenly bodies could be described at least as easily on the assumption that the earth revolves round the sun. Ptolemy was quite open-minded on the question, and only rejected the movement of the earth on what seemed to be sound physical grounds, such as the failure of the surface of the earth to leave the clouds behind. He thought that if the earth were rotating on its axis, then the clouds ought to be continually slipping back, because there was no rigid connection between them and the earth.

Ptolemy's treatise remained the standard work on astronomy for fourteen hundred years. It was thoroughly worthy of the prodigious fame it acquired, but its assumption of the fixity of the earth fitted in with the static outlook of society in Roman and medieval times.

Rather more progress was made in astronomy in this period in the new Arabian civilization, especially in observational astronomy. Ptolemy's treatise was translated into Arabic on the order of the Caliph Al-Mamun about A.D. 827. Notable observatories were established in the Middle East, of which that founded by Ulugh Begh, the grandson of Tamberlaine, at Samarkand in 1420, became particularly famous. His astronomers produced the first catalogue of stars which improved on Ptolemy, and they were the first to record stellar positions to an accuracy of minutes of a degree. The influence of Arabian astronomers is seen in the many astronomical terms which have come from them, such as zenith, nadir and almanac, and the names of certain stars, such as Aldebaran and Betelgeuse. The most important influence of the Arabian astronomers was indirect,

through their introduction of the Indian or common numeral system, and the new Arabian science of algebra, which facilitated astronomical calculation and research.

The authority of Ptolemy remained unchallenged through Arabian as well as Roman and medieval times. It was not superseded until the Renaissance and the discovery of America, which finally broke up the old static view of the universe. The new outlook took motion and change for granted and was thereby fitted to recognize it, even in forms which were difficult to perceive, such as the motion of the earth. It enabled astronomers to advance beyond Ptolemy.

The major step was taken by the Polish astronomer Copernicus, who introduced the dynamic spirit of the new age into astronomy. It is significant that he came from the maritime Baltic, and started his higher education, at the age of nineteen, in 1492, the very year in which Columbus discovered America.

This provided the concrete proof that the sphericity or roundness of the earth is real, and not a mere figment of the mathematical imagination. After this shock to ancient ideas, it became far easier to inject the new Renaissance spirit of motion into the behaviour of the earth itself.

Copernicus's achievement was more in changing the outlook in astronomy, than in advancing it technically. He was careful to put forward the view that the earth is in motion, not as his own idea, but as a revival of the ancient ideas of Heraclides and Aristarchus.

The final establishment of the Copernican theory, which converted it from an attractive intellectual hypo-

thesis into the foundation of modern astronomy, and of the modern view of man's place in nature, required immense investigations both in observational and theoretical astronomy. The two who contributed most to these were Tycho Brahe and Johannes Kepler, with a description of whose life and work this book begins.

The third subject, Edmond Halley, was born only twenty-six years after the death of Kepler, but he belongs to another age. He was a magnificent representative of the new interest in astronomy of the mercantile and overseas trading society, which arose in England after the discovery of America. His forecast of the date of the return of the famous comet named after him was the first major confirmation of Newton's theory of gravitation. In the course of improving the science of navigation he virtually invented the new science of geophysics, which is now developed on the scale of world-collaboration in the International Geophysical Year.

William Herschel, following on Halley's discovery that the 'fixed' stars may move, founded modern cosmology. He revolutionized knowledge of the structure of the universe by solving the problems of the construction and use of giant telescopes.

During the nineteenth century, the lead in observational astronomy passed to the United States, where greater resources were available for the construction of increasingly expensive instruments, and a more suitable climate prevailed for their use. The more detailed knowledge of individual stars collected by the newer instruments led to further study of their physical constitution. This new physical knowledge of the stars was in particular

reviewed and analysed by Henry Norris Russell, the outstanding American astronomer. He prepared the way for a deeper understanding of the internal structure and evolution of the stars.

The foundation of the modern theories of the internal structure and evolution of the stars was laid by Arthur Stanley Eddington. He showed how, with the aid of modern knowledge of the structure of the atom, and the possibility of the release of atomic energy, many of the chief features of stars could be explained, and reasonable suggestions made about their origin, mechanism and evolutionary history. It is from his pioneer work and methods, together with the growing knowledge of physics, that the younger generation of astronomers is advancing with inspiring speed into still deeper and more detailed discoveries about the nature of the stars and the universe.

REFERENCES

Introduction to Astronomy, by Cecilia Payne-Gaposchkin. Eyre and Spottiswoode.

The History of Astronomy, by Giorgio Abetti. Sidgwick and Jackson.

A Short History of Astronomy, by Arthur Berry. John Murray: 1898.

Six Great Scientists (Copernicus, Galileo, Newton, Darwin, Marie Curie, Einstein), by J. G. Crowther. Hamish Hamilton:

I

TYCHO BRAHE

1546–1601

THE modern conception of the world was first expressed by Nicolaus Copernicus, when he showed that the movements of the planets could be described more simply on the principle that the earth went round the sun, and not the sun round the earth. The decision to adopt this principle was the most striking single event of the Renaissance. It changed man's attitude towards the universe, removing the earth and himself, which he had egotistically placed at its centre, to a modest position as dependents of the sun, and indeed of the galaxy and the rest of nature.

The greatness of Copernicus's flight of imagination cannot be exaggerated, but putting forward his principle was one thing; proving it was true was another. Copernicus gave good arguments for accepting it, but he was unable to make sufficiently accurate practical observations and predictions to prove it conclusively.

Navigators did not find that the tables based on his theory and observations were a sufficient practical advance to justify their taking the trouble of learning the new-fangled theory. They preferred to use the old tables and ideas, which might not be so accurate, but were thoroughly familiar. Astronomers hesitated to accept

the new theory, as the form in which it was stated by Copernicus had some grave defects.

Copernicus held that the planets went round the sun in perfect circles. But it was evident that the orbits of the planets could not be perfect circles. Also, the centres of the various circles in which the planets were supposed to revolve were not in the same place: they did not coincide. These were real scientific difficulties, which were not resolved until after Copernicus's day.

It was not possible to prove the new theory conclusively until much more accurate astronomical observations had been made. This required the invention of the modern method of making observations. Hitherto, practical astronomers, and Copernicus himself, had not developed a science of observation. They thought that occasional observations, now and then, were sufficient. This notion died extraordinarily hard.

The first to escape from it was Tycho Brahe, who thereby became the founder of the modern observational astronomy. Tycho was a Dane, and a typical descendant of the Northmen, with their executive genius. It would have been easy to imagine him, in earlier times, leading bands of Vikings in raids on foreign shores. He had transferred the tradition of invasion and conquest of other peoples' countries to the unknown regions of the heavens. He was not unlike Rutherford in his masterful manner and appearance. Their ancestors came from North Western Europe, and they both combined extraordinary practical skill with exceptional powers for recognizing good ideas and talent, and organizing and directing others.

After Tycho had grasped the shortcomings of practical astronomy he started a complete reconstruction of the subject. He decided that no astronomical data should be taken for granted, but that all should be checked and re-measured. He set out to make a new inventory of the heavens. To do this he devised better instruments, and founded the modern method of making observations. He introduced the systematic correction of errors in each observation arising from faults in the instrument.

He improved the accuracy with which angles of a small fraction of a degree could be measured. He devised an eye-piece consisting of slits which made the sighting of astronomical instruments on a star more accurate. He made the determination of the position of the sun, which is fundamental in astronomy, a hundred times more accurate. He pointed out that besides making a sufficient number of observations, they should be carried out over a sufficient period of time. For instance, Mars would have to be observed regularly for at least four years, and Saturn for at least thirty years to obtain a complete record of one of their respective cycles of movement in the heavens.

From the scientific point of view, Tycho's development of method in observation was as important as Copernicus's new theory. It represented as great and subtle a break with the past, though it was less obvious because of its technical nature.

The establishment of the modern outlook in practical astronomy required great strength of personality, social authority and wealth, as well as the highest technical skill. Tycho was descended from feudal landowners who

had flourished in Denmark and Sweden for centuries. He was of noble though not titled standing, corresponding to an old English squire.

Tycho's father, Otto Brahe, became governor of the castle at Helsingborg, which is on the now Swedish side of the narrow channel between Denmark and Sweden, opposite to Elsinore, the scene of Hamlet's tragedy. His wife Beate Bille, who had already borne him one child, gave birth to twins on 14 December 1546, at the family house at Knudstrup in the south of Sweden, which then belonged to Denmark. Only one of the twins, Tyge, survived. He became the famous astronomer, and then was known by his Latin name Tycho.

Otto Brahe's brother Jörgen was childless, so Otto promised that if he had a son he would give him to his brother to bring up as an adopted son. When Tycho was born, Jörgen accordingly demanded him, but Otto tried to avoid giving him up, so Jörgen kidnapped him. Tycho's parents did not protest very much, for they knew that Jörgen would bring him up well, and bequeath his fortune to him.

The rough justice worked out quite well. Jörgen educated Tycho carefully. He secured a good tutor and had him taught Latin from the age of seven. Tycho mastered the international language. He spoke and wrote it fluently, and composed many Latin verses, some of which were good. He became an effective writer as well as a great astronomer. He could hold his own in the literary field.

His uncle sent him at the age of twelve to Copenhagen University to study rhetoric and philosophy, with

the intention of educating him to be a statesman. At this time, astrology was still a subject of almost universal interest and belief. Brahe shared the general interest, and being gifted acquired an exceptional skill in it. Through this he learned something of astronomy.

Then, on 21 August 1560, when he was thirteen, a partial eclipse was observed at Copenhagen. It occurred at the time the astronomers and astrologers had predicted. This event produced in the aroused mind of the expectant boy the deepest impression of Tycho's life. It struck him that the predicting of eclipses so far in advance had something of the divine power. He was seized with a passion for astronomy, and finding the available books inadequate, he spent two Joachimsthalers. that is, two original silver dollars, on buying a Latin translation of Ptolemy's works. The actual copy is in the University Library at Prague. Tycho wrote in it that he bought it on the last day of November 1560. He was not yet fourteen years old, but he had obtained a copy of the chief astronomical work of the ancient world.

Tycho spent three years at Copenhagen, eagerly studying astronomy and mathematics. His uncle then sent him to Leipzig University to broaden his studies and experience, in the care of a tutor only four years his senior, who became a life-long friend and a distinguished historian. This was A. S. Vedel, the translator of *Saxo-Grammaticus*, and other sources of Danish history. Vedel had been instructed to guide Tycho in the study of law in the preparation for statesmanship, but he was unable to prevent him from at once making

the acquaintance of the mathematicians of the university. Within three months Tycho learned important knowledge of practical astronomy from one of them. He spent his money on astronomical books and instruments, though he had to account for everything to Vedel. He learned the names of the constellations from a small celestial globe. At first he hid this globe from Vedel, bringing it out only when his tutor was asleep.

Vedel, who was a very conscientious young man, felt that Tycho was disobeying instructions, and disapproved of his behaviour. For a time, relations between them became strained. As was to be so often the case, Tycho had his way. Vedel perceived that Tycho was very able, and his passion for astronomy was profound.

While at Leipzig, Tycho obtained copies of the planetary tables compiled under the direction of King Alphonso of Castile in the thirteenth century, and the Prussian tables compiled by one of Copernicus's disciples. He learned how to compute the positions of the planets in the sky from the data in these tables, and detected mistakes in the use of the tables by leading astronomers. He found that the places of the planets according to the computations were often widely different from where they were observed to be. Through this experience, at the age of sixteen, he first grasped the fact that the most pressing need of astronomy was systematic observation, in order to eliminate or reduce the manifold errors in the tables.

He started systematic observations before he was seventeen years old, being launched on this by the occasion of the conjunction of Saturn and Jupiter in August

1563. This event was considered of great astrological importance, and was awaited with intense interest. His first recorded observation was on 17 August, made with nothing more than an ordinary pair of compasses. He noted that on 24 August the two planets were very close together.

The date of the event, as predicted from the Alphonsine tables, was a whole month in error, while the new Prussian tables were still several days out. Tycho was more than ever impressed with the need for better observations. He acquired more instruments, such as the cross-staff used by the navigators who explored the New World.

When Tycho got his cross-staff, Vedel had not yet acquiesced in his astronomical studies, so he first used it, like his celestial globe, when his tutor was asleep. He found that the instrument had faults of design which produced systematic errors, so he tried to get Vedel to allow him money to buy a better one, but Vedel would not agree. Tycho thereupon compiled a table by which the observations could be corrected for the systematic errors arising from the instrument.

This was the beginning of the modern scientific method in observational astronomy. Tycho started it when he was seventeen. As Kepler said, the restoration of astronomy was 'by that Phoenix of astronomers, Tycho, first conceived and determined on in the year 1564'.

In the following year war between Denmark and Sweden broke out, and Tycho returned home. His uncle became vice-admiral of the Danish Navy, and a member of the

king's circle. While riding out of Copenhagen Castle over the bridge, the king fell into the surrounding water. Jörgen jumped in to help him out, caught a chill and died.

After the death of his uncle Tycho no longer felt under an obligation to become a statesman. He went abroad again to pursue his studies, this time like Hamlet and many other young Danes, to Wittenberg University. When he arrived he found his former tutor Vedel had already made his way there. Tycho, also like Hamlet, had dealings with the noble families of Rosencrantz and Guildenstern, to which he was related.

Wittenberg had become one of the most flourishing centres of mathematics and the astronomy and astrology associated with it. This was due to the influence of the Protestant theologian and philosopher Melanchthon, who had inspired the foundation of two chairs of mathematics in the university. His own son-in-law Peucer was professor of medicine and a notable mathematician.

While Tycho was still at Leipzig he had foretold Peucer's life from the stars, saying that he would suffer great misfortunes and imprisonment, but would be freed at the age of about sixty. Ten years later, Peucer was ejected from his chair on suspicion of Calvinism, and was rigorously imprisoned for twelve years, being freed ultimately at about the age of sixty.

The fame of Wittenberg as a centre of astrology and alchemy is reflected in Marlowe's *Faust*, whose hero is depicted as a Wittenberg student.

Soon after Tycho arrived in Wittenberg the plague broke out, so he moved to Rostock on the Baltic coast,

which specialized in astrology and alchemy. Shortly after Tycho's arrival, there was a lunar eclipse, on 28 October 1566. He announced that this foretold the death of Sultan Soliman. Unfortunately it turned out that Soliman died before the eclipse, but Tycho was not abashed.

Some weeks later he became involved in a quarrel with a young Danish nobleman at a party to celebrate a betrothal. The young men considered that honour demanded a duel. This was fought with swords without lights on a pitch-dark night. Tycho lost part of his nose, and ever after wore a small plate on it, made of electron an alloy of gold and silver. He carried ointment in a vial, which he applied from time to time, no doubt to keep the plate in position and soothe irritation. His portraits show that there was something unusual about his nose.

Tycho subsequently became friendly with the duellist. His quick temper and action, and also his reduction of the incident to its proper perspective, in spite of his permanent disfigurement, were typical of his character. He could be violent and domineering, but his better judgment usually, though not always, got the upper hand.

When Tycho returned home on visits he was well received by his relatives and friends, but there was much disapproval of his studies of the stars. They were considered a waste of time and beneath his social position. Nevertheless, some influential persons thought highly of them. In 1568, when Tycho was twenty-one, the King of Denmark, Frederick II, granted him the first

canonry to become vacant at Roskilde, the chief cathedral in Denmark. At the Reformation the king had confiscated the incomes for these posts. During the next hundred years the incomes were bestowed as the king thought fit, and were used especially for providing stipends for scholars. They were virtually research fellowships, with no religious duties. Like Copernicus, Tycho was provided in his early twenties with the income from a canonry, with virtually no duties, which guaranteed him a livelihood and leisure for the rest of his life. The effects of the Reformation in transferring church funds to the support of science and learning were very important.

Tycho now went to such universities as he thought might provide him with special knowledge He studied at Basle in Switzerland, and then at Augsburg, the German commercial, technical and cultural centre which developed after the Reformation. It had unequalled craftsmen and instrument makers, whose ingenious contrivances were famous. Even today, in the middle of the twentieth century, some of the best diesel engines for British Railways are built in collaboration with Augsburg firms. It was the headquarters of the enormously rich financiers, the Fuggers. The concentration of wealth stimulated luxury and culture. The well-to-do mayor and aldermen dabbled in astrology and astronomy, and desired to have some fine instruments for making astronomical observations.

With his practical talent Tycho made use of these circumstances. One day, while he was engaged in calculating how large an instrument would have to be to attain

a certain degree of accuracy, an ex-mayor with astronomical interests happened to drop in. Tycho discussed the problem with him, and his friend undertook to defray the cost of making a huge quadrant of 19 feet radius. It was to be made by the best of the craftsmen of Augsburg, and was to be erected in the garden of the ex-mayor's country house.

In addition to this, Tycho designed a remarkable instrument for measuring angles in any plane, which he presented to his friend. Before he left Augsburg he ordered the construction of a huge celestial globe five feet in diameter. This was ultimately covered with gilt brass plates, on which the positions of the stars and equator and other data were marked.

Tycho's contact with Augsburg was an important factor in his achievement. It placed at his disposal the considerable advances in technique which foreshadowed the development of industrialism, and which were essential in enabling him to make better astronomical instruments than his predecessors.

He left Augsburg in 1570, apparently owing to the illness of his father, who died in the following year. Tycho inherited half of the family property. He did not find his father's relatives sympathetic, but his mother's brother, Steen Bille, appreciated his scientific interests. After the Reformation Bille had been ordered to take charge of a Benedictine monastery, on the ground that it was the scene of 'ungodly life'. He was to continue divine service according to Lutheran ritual, and expel 'all superfluous learned and useless people'. Bille was interested in technology and alchemy. He introduced

paper-making and glass-making into Denmark. Tycho went to live with him, and was provided with an out-house of the monastery for use as a laboratory.

During the next two years Tycho devoted himself to alchemy, which on one side was related to the processes of chemistry, and on the other to astrology. Tycho called alchemy 'terrestrial astronomy'. Later on, as an alchemist, he made elixirs for Emperor Rudolph II, to protect him from the plague. Astrology and alchemy were related, and astrologers were often alchemists. According to astrology, the ruling influences on the universe were exerted by the planets; and according to alchemy, a similar influence was exerted by the metals. These were regarded as representatives of the planets, and had the same symbols; as, for instance, the sun and gold, Venus and silver, Mars and iron, Saturn and lead. The planet Mercury and the metal mercury still have the same name.

The extraordinary event which finally settled the direction of Tycho's life occurred while he was deep in his alchemical researches. On the evening of 11 November 1572, when returning from his laboratory to the house for supper, he casually glanced at the sky, and was startled to see a very bright star, as bright as Venus, in the constellation of Cassiopeia, in a place where he well knew there was no bright star before. With the natural caution of a born observer, he asked servants with him whether they saw it, and then he stopped passing peasants, and asked them. All were certain they could see the star, so Tycho felt reassured that he was not suffering from an illusion.

He had recently made a new sextant with arms five and a half feet long, and with it he set about determining the exact position of the star. He pursued this through the winter, measuring its distance from the well-known stars in Cassiopeia. He could detect no movement of the star relative to the fixed stars. It looked and twinkled like an ordinary star. For about one month it remained so bright that it could be seen even in broad daylight. Then it slowly declined, remaining visible for about eighteen months. Tycho estimated its brightness by comparison with the stars in Cassiopeia, and he noted a gradual change in colour, from white to yellow, and then red.

Hitherto, all new stars had proved to be comets. Tycho's observations showed that this one could not be a comet, because it did not move relative to the fixed stars. It appeared, in fact, to be a new 'fixed' star. Nothing of the kind was known to European astronomers.

Tycho called his star the Nova. It was the first new star to be observed in modern European times, and the first of the very important type called *super-novae*. These are now known to be caused by the explosion of a whole star in the manner of a hydrogen bomb. Its outer parts are ejected with prodigious violence, and sometimes form a nebula which can be seen to be still expanding, centuries later, at a speed of many millions of miles a day. Some of the material of the star is subject to extreme pressures by the atomic explosion, and it is thought that under these conditions the heavy elements, such as uranium and iron, are synthesized out of the lighter elements. It is believed, too, that the violent

agitation of the matter blown out in the super-nova explosion may generate radio waves, and that the radio stars detected by modern radio telescopes are in some cases the debris of super-novae. One of the most intense sources of radio waves in the sky is in Cassiopeia, and this may perhaps be the debris of Tycho's star, now operating as a cosmic radio transmitter.

Early in 1573 Tycho wrote an account of the new star, which he showed to friends at Copenhagen University. They had not yet heard of it, and thought he was joking, so on the first clear night he pointed it out to them. They were astonished, and advised him to publish his account. Tycho demurred, on the ground that it was unbecoming in a nobleman to write books. After he returned home, however, fantastic descriptions of the new star began to reach him from various parts of Europe. He felt that a more accurate account was badly needed, so he changed his mind and published his own. It appeared in 1573, in a short book of about 100 pages.

Tycho had complete confidence in the accuracy of his observations. He uncompromisingly put forward the view, which he believed was in opposition to all the philosophers, that the new star proved that new bodies could be generated in the region of the fixed stars, which hitherto had been considered to be unchangeable. He said that if the star could come into existence, and change in brightness and colour, then it was not absurd to suppose that in the future it might pass away. Things which appeared after the creation should disappear before the end of the world. His comments suggested that stars

could have a history: coming into existence, changing, and passing away.

This idea was in flat contradiction with the ancient and accepted view. The fixed stars were supposed to be part of an absolutely unchanging region, which was created as it is, and would continue exactly like that to all eternity. The belief that the fixed stars never changed had been a cause of the neglect of their observation. The Arabian astronomers, for example, were only interested in observing the planets, which moved.

The discovery that a 'fixed' star could change was a severe blow to the old Aristotelian view. Tycho's little book, published before he was twenty-seven, was one of the intellectual peaks which separate modern from medieval times. The fact that the fixed stars could change showed the paramount need for a new star catalogue, to record other major changes since Hipparchus and Ptolemy had made theirs more than fourteen hundred years before. Tycho was prepared both in mind and technique to perceive the tremendous implications of the new star and he explained these in much the same magisterial manner as Rutherford in drawing revolutionary conclusions from his experiments on the atom.

Tycho saw that if the stars changed then the whole universe might be changing. It was not as men had thought it was, and everything had to be looked at afresh. He panted to explore the unknown new world.

While Tycho was engaged in creating the modern outlook, he still had a very lively interest in the one that was about to pass away. Together with the inspired

observations and scientific interpretations, he included in his book a careful discussion of the astrological implications of the new star. He said this was very difficult because the event was so unusual. The only report of a new star known to him was that of Hipparchus in 125 B.C. (Modern opinion is that this was probably a comet.) Hipparchus's star had, says Tycho, been followed by disasters amongst Jews and Gentiles, so he foretold that the new star portended disasters for the whole of Europe. In its first phase it had looked like Venus and had been beneficent, but then it became red like Mars, portending wars, seditions and deaths of princes; finally, it became like Saturn, portending famine, imprisonment and sadness. He no doubt had in mind the recent Massacre of St. Bartholomew, and the religious wars.

Tycho was not satisfied with his limited facilities. He believed he could find better opportunities for research abroad, and decided to leave Denmark as soon as he could. He was delayed in this by falling in love with a peasant girl called Christine, whose surname is unknown. They were never married in church. After his death his relatives, who had not recognized his marriage but were now exploiting his fame, declared that his children were legitimate, according to ancient Danish law. Christine bore Tycho eight children, including two sons. As she had been a bondwoman, there were difficulties over the inheritance of Tycho's estate by their children. Tycho became worried by this problem because of the disposal of his incomparable collection of observations and instruments. None of his children became sufficiently good astronomers to qualify as his

scientific heir, though his son-in-law Tengnagel, who had worked with him, disputed the scientific inheritance which Tycho bequeathed on his deathbed to Kepler.

Tycho's work on the new star confirmed his reputation. His friends in Copenhagen persuaded the university to invite him to lecture, but Tycho refused until the invitation was reinforced by a request from the king. He spent nearly two years preparing his course, introducing it with a lecture in which he expounded his views on the history and importance of mathematics, astronomy and astrology. He said that one of the reasons why the Greeks excelled in geometry was that they could start studying it in their infancy, because the subject was created in their own language, so that they did not have to waste the best years of their youth on the study of ancient languages and grammar. He regarded Copernicus as a second Ptolemy, and the great restorer of astronomy, though he was not able to accept all the features of his system.

He said that the utility of astronomy was evident, for no nation could live without a proper method of measuring time. Astronomy also exalted the mind, raising it above trivial to heavenly things. In particular, the movement of the stars threw light on human fate. It was not possible to deny their influence without disbelieving in the wisdom of God. The regular motions of the heavens could not have been created without a purpose. The sun caused the seasons. Sailors and peasants had noticed the influence of the stars on the weather. As man is made from the same elements as nature, he also is subject to the influence of the stars.

Nevertheless, as God had the power of changing the course of nature by His will, so also man had in him something that made it not impossible for him to resist the influence of the stars. It was therefore useful to him to have warning of possible evils.

After delivering his lectures Tycho left Denmark in 1575 on a long astronomical tour. He called on William IV, Landgrave of Hesse at Cassel, who was second only to himself among contemporary astronomers, and then proceeded to Frankfurt, Basle, Venice and Augsburg. He went to Ratisbon to meet scientific men attending the coronation of Rudolph II, King of Hungary and Bohemia, as Roman Emperor. He planned to settle abroad, where conditions for astronomical study seemed more promising than in Denmark.

The King of Denmark, Frederick II, had recently sent an embassy to the Landgrave of Hesse. The royal astronomer had been particularly happy to talk about Tycho and astronomy with the Danish emissaries. He emphasized the importance of Tycho's work, and the national duty of Denmark to retain so promising a subject, who would bring credit to his king and country.

Frederick II, impressed by the Landgrave's opinion, offered Tycho various castles, but Tycho declined them, and went on with his preparations for emigration. The king now sent for him, and said that perhaps he had not accepted his offers because he feared his studies would be disturbed by social interruptions. He had recently been at Elsinore, where he was building a castle, and he had noticed the nearby island of Hveen. It struck him that a house there would be free from disturbance, so he

offered him possession of the island for life, and means for the construction of a building.

Tycho consulted his friends, who strongly advised him to accept. He did so, and the king immediately conferred on him an annual pension of 500 'good old thalers'.

The island of Hveen is about fourteen miles north of Copenhagen, and three miles from the Swedish coast. It has steep white cliffs and a pleasant slightly undulating surface. Tycho was given feudal rights over the island, so that the peasants there were bound to him. He exerted his rights energetically with full feudal gusto, and accumulated much resentment among his tenants.

The king gave 400 thalers towards the building of the house and observatory, but Tycho was to find his own materials and labour, which he could command from the local population. He chose a site near the centre of the island. The foundation stone was laid at a good astrological moment on 8 August 1576, and celebrated by solemn libations in various wines.

The construction was carried out by the architect Hans van Stenwinchel of Emden, according to Tycho's ideas and design.

The astronomer was not yet thirty years old, but Copenhagen University offered him its rectorship, which had never before been offered to anyone who was not a professor. Nevertheless, Tycho refused it. On his thirtieth birthday, on 14 December 1576, he started a fundamental series of observations on the sun, which he pursued systematically for more than twenty years.

The house and observatory were in effect a great

institution specially designed and built for astronomical research. It probably influenced Bacon when he composed his description of Salomon's House in *New Atlantis*. Tycho called it Uraniborg, the 'city of the heavens'. It was at the centre of a square court, the corners of which were placed at the points of the compass. Each wall of the court was about 250 feet long. Gates were placed at the east and west corners. Over the gates English mastiffs were housed, to give notice of the approach of strangers. Their behaviour contributed to Tycho's subsequent unpopularity.

Rooms were built in the north corner of the court for Tycho's printing press. He sometimes composed verses in order to keep his printer busy when the supply of scientific copy had run out. He was not without poetic talent. When discussing the propriety of leaving his native land to pursue astronomy, he once wrote: 'any soil was a country to the brave, and the heavens were everywhere overhead'.

In the south corner were rooms for his servants, and under these his prison, where refractory tenants were kept.

The house, Uraniborg, was surrounded by an orchard containing three hundred fruit trees. It was built of red bricks with sand-stone ornaments, in the Gothic Renaissance style, and had a profound influence on Scandinavian architecture. It was about 100 feet long, with an octagonal pavilion on the top, carrying a weather-vane which was 62 feet above the ground. Within the pavilion there was a dial in the ceiling, showing the time, and the direction of the wind. The top of the building was

surrounded with platforms, pillars and galleries on which observational instruments could be mounted.

The ground-floor rooms were arranged round a central fountain. They included living accommodation and a number of guest-rooms. There was a large circular library, and several aviaries. The library contained Tycho's huge 5-foot Augsburg globe, a fine collection of books, portraits of astronomers among whom Copernicus and the Landgrave were prominent, and a museum of instruments and curios. Tycho particularly treasured a small instrument which Copernicus had made with his own hands. There was a portrait of George Buchanan, the Scottish theologian and politician, who probably met Tycho in Denmark in 1571.

Tycho was very proud of his large quadrant or quarter-circle, made of brass strip 2 inches wide, and 6¾ feet in radius. A hole in the wall was placed at the centre of the quadrant, and an eyepiece that slid round the strip was pushed by the observer until the star and the hole appeared in line. Tycho commissioned leading artists to paint pictures on the wall beside the quadrant of himself, his chief instruments and his laboratories. Three assistants were shown at work with the quadrant, one observing the star through the eyepiece, the second noting the time on clocks and the third seated at a table taking down the readings.

As the scope of his investigations and the number of astronomers who came to work at Uraniborg increased, Tycho required more instruments, both for extending the variety of observations and for independent checking. Some nine years later he built a second smaller

observatory on a hill just outside the court of Uraniborg. It contained five instrument rooms, and a central study.

Only the roofs of the rooms were above ground, so that the instruments were protected from the wind and weather. He called this second observatory Stjerneborg, 'the city of the stars'. On the ceiling of the study was painted a picture of Tycho's system of the world, and on the walls, leading astronomers, including Ptolemy, Copernicus and himself. There was also a portrait of Tychonides, an astronomer as yet unborn, who was to inherit and extend his own achievements. Under it was placed a legend expressing the hope that Tychonides would be worthy of his great ancestor. Though none of Tycho's descendants fulfilled this hope, Tycho was indeed destined to have in Kepler a scientific heir as great as the Tychonides he had envisaged.

The cost of building this institution was large. Tycho estimated it at 75,000 thalers. The king gave him many grants and estates, from which Tycho took as much, and gave as little, as he could. When he received the canonry of Roskilde, he did not make the customary provision for the widow of his predecessor until he was ordered to do so by the king. He failed in his obligation to keep the lighthouse on Hveen in order. He imprisoned his tenants on slight pretexts. As part of his feudal way of life, he had a jester, who sat at his feet at meal times, and was fed on morsels that Tycho cast to him; he was supposed to have second sight.

Uraniborg was a self-supporting feudal establishment, providing its own food, materials and labour. Tycho devoted considerable attention to the development of

Hveen. He constructed a system of fifty ponds for cultivating fish. He built a water-mill, a corn-mill and a paper-mill.

In spite of all his fame and improvements he left a legacy of hatred in the island population. After he left Hveen, Uraniborg and Stjerneborg rapidly fell into decay, and the peasants whom he had driven so hard looted them for building material. Before long, scarcely a relic of the great institution remained.

Tycho's prestige arose in the first place from his fame as an astrologer, and his authority from his social position as a feudal lord, as well as his scientific skill. His astrological interpretation of the star of 1572 was widely regarded as a forecast of the Thirty Years' War. He said that 1632 would be a year of tremendous events and crisis in the struggle. When Gustavus Adolphus achieved his greatest victories, and also died, in that year, many believed that Tycho had forecast these events. He worked out the fates of the members of the King of Denmark's family, according to the stars.

Soon after he had built Uraniborg, Tycho became absorbed in studying the great comet that appeared in 1577. He first saw it on an evening, when he was at one of his ponds, trying to catch fish for supper. Soon after sunset, the comet developed a magnificent tail. Tycho started a series of observations which proved that the comet was very distant, and could not possibly be in the atmosphere. This was contrary to Aristotelian science, which held that comets were atmospheric phenomena.

Tycho's observations on this comet strengthened his

belief that astronomy required a complete reformation. He decided to write a great work, an *Introduction to the New Astronomy*, setting forth the new ideas, and the observational evidence for them. The first volume was to deal with the new star of 1572, and the second with the comet of 1577.

Tycho printed both volumes in his own printing press at Uraniborg, and published the volume on the comet first, in 1588. In this volume, he discussed the implications of the new comet for the structure of the universe. The Ptolemaic system must be abandoned as too complicated. He could not accept the new system of that great man, Copernicus, because, though it was mathematically sound, it was contrary to the laws of physics, which hold that the earth is sluggish and unfit to move; it was also contrary to the Scriptures. He had tried to find a system which would satisfy both mathematics and physics, and also not offend theologians. He described how in 1583 he had had a happy inspiration for a solution of the problem. According to his new system, the earth was the centre of the world, with the moon and sun, and 'fixed' stars revolving round it. The other planets revolved round the sun.

His departure from the ancient system was less radical than Copernicus's, but immediately it was more effective. What Copernicus could not carry through in one step, Tycho and Kepler were able to achieve in two.

Tycho sent copies of his book to Saville, the brother of the founder of the chairs of mathematics and astronomy at Oxford. He had asked Saville in 1586 whether there were any good poets in England who could write an

epigram in praise of his portrait or works. Marlowe and Shakespeare were twenty-two years old at the time.

In 1590, King James, then James VI of Scotland, visited him at Uraniborg, during a voyage to Copenhagen to secure the hand of his wife Anne, one of the Danish king's daughters. James was pleased to see the portrait of Buchanan, and discussed astronomical questions with Tycho, subsequently sending him two Latin epigrams, which Tycho proudly placed at the beginning of his *New Astronomy*. James also presented Tycho with two English mastiffs, no doubt noticing his taste for the breed.

Tycho's great patron and benefactor King Frederick II died prematurely in 1588. His son Christian was a boy of eleven, so affairs of state during his minority were managed by a council of four noblemen. These were not disposed to allow Tycho to continue to enjoy his great privileges, and from this time his position declined. The young king, who was carefully educated, was interested in Tycho, but was prevented from getting to know him well. When he reached his majority and was crowned, he had become interested in other things. He curtailed Tycho's income, and became impatient with his arrogance. After a number of disagreements, law-suits and quarrels, the king cancelled his annual pension.

Tycho could no longer conduct Uraniborg on the old lines, so he decided to leave. He was not the man to adapt himself to what he regarded as second-class conditions. He moved to Copenhagen, taking his library, smaller instruments, chemical apparatus and printing press with him. Later in the year he moved to Rostock, with

his family, assistants and equipment, a group of about twenty persons.

While at Rostock Tycho wrote to the Danish king, indicating that he was prepared to return to Denmark and resume his work, if restored to favour. The king replied unsympathetically, saying that his letter was not without great audacity and want of sense, and written in the manner of an equal.

Tycho now sought patronage among several heads of European states. He wrote a description of his scientific instruments, pointing out the advantages of their design. Among other features, they had been designed so that they could be easily dismantled and transported. He added a brief sketch of his life and scientific achievements, including his improved data on the sun's motion; the discovery of a new irregularity in the moon's motion; the variability in the inclination of the moon's orbit; the accurate observation of the positions of one thousand stars; the proof that comets were further away from the earth than the moon, and a vast collection of exact observations of the planets, from which new and more accurate tables of their motions could be calculated.

Tycho printed and bound this volume sumptuously. He dedicated it to Emperor Rudolph II, whose court was in Prague, hoping that he might secure an invitation to settle there. He also bound a manuscript copy of his catalogue of the fixed stars, dedicated it to Rudolph, and sent it to him as a New Year's gift.

Rudolph informed Tycho that he would be welcome in Prague, and would lack nothing for his researches. The emperor was a small, reserved man, a devotee of

astrology and alchemy, and a great art collector. He rarely left the huge castle at Prague, the halls of which he filled with art treasures sought by his agents in many countries. He was bored with politics, with the consequence that the management of affairs drifted into the hands of his officials. Rudolph's lack of interest in affairs produced a regime of relative tolerance, for he was not personally interested in enforcing the official Catholic policy.

Tycho arrived in Prague in 1599, and was splendidly received by Rudolph, who bestowed on him a higher pension than on any other member of his court. Besides other grants, he gave him a castle, about twenty miles from Prague, as a residence and observatory. Owing to the beauty of its surroundings it was called Nove Benatky, or New Venice.

Tycho set up the instruments he had brought with him and started making observations. But he never really settled down in Bohemia. He had less equipment, and fewer assistants than at Uraniborg. There were attacks of plague which often caused him and his staff to move, and also the emperor and his court.

Tycho had much difficulty in collecting the grants that had been promised to him. He plodded on with his observations as best he could, and looked for astronomers to join him. This led him to by far the greatest of his achievements in Bohemia: the securing of Kepler's collaboration.

Kepler was twenty-five years Tycho's junior. In 1596, at the age of twenty-five, he published his first great work, the *Mystery of the Universe*. He sent copies to Tycho and

other leading astronomers. Tycho congratulated him on it, and enthusiastically invited him to Prague, but regretting that he had preferred Copernicus's system to his own. In a marginal note on the letter Kepler wrote in Latin: 'Everyone loves himself.'

Kepler, who was a Protestant, had an appointment at Graz in Austria. He was presently forced to leave Graz, so he explored the possibilities of coming to Prague to work with Tycho. After Tycho had been informed of the situation, he wrote to Kepler from Benatky that he would be more than willing to have his assistance.

Kepler arrived in Prague in February 1600. Tycho assigned to him the investigation of the motion of Mars, which ultimately led Kepler to his discovery of the three laws of planetary motion.

Nevertheless, Kepler did not feel comfortable. He thought that Tycho regarded him as an assistant rather than a collaborator of independent scientific standing. A period of difficult negotiations started, during which Kepler left Prague and looked for posts elsewhere. Tycho made efforts to meet his demands, and solicited the emperor for an appointment for him. Kepler returned to Prague, and the emperor commissioned him to work on the calculation of the new planetary tables based on Tycho's observations, which were to be called the Rudolphine Tables.

The arrangements were made only just in time. In October 1601 Tycho was taken ill while at supper with one of the court nobles. After a few days of sleeplessness and fever, he felt the approach of death. He sent for

members of his family and Kepler, and he begged Kepler to complete the Rudolphine Tables, adding the hope that he would base them on his system of the world rather than the Copernican.

Tycho died on 24 October, and was interred with great honour in the Tynskykostel, a church where some Protestant forms were still tolerated.

He was not yet fifty-five years old when he died, as it were, in exile. Yet his exile provided the crown of all his work, as it enabled him to make Kepler his scientific heir, and so ensure the most glorious consummation of the revolution of astronomy, based on Copernicus's theory and his own observations.

REFERENCES

Tycho Brahe, by J. L. E. Dreyer. Adam and Charles Black: 1890.
The Redemption of Tycho Brahe, by Max Brod.

II

JOHANNES KEPLER

1571–1630

KEPLER extracted the meaning of Tycho Brahe's new observations of the planets by one of the most brilliant efforts of genius. He conceived and proved that the planets must revolve round the sun, not in circles but in ellipses; and that the sun must be at one of the foci. (An ellipse is an oval curve easily drawn by tying the ends of a piece of string to two pins stuck in a table, and then tracing the curve made by a pencil which is moved so that the string is kept taut. The pins are at the two foci of the ellipse.)

For more than two thousand years it had been believed that the planets and stars necessarily revolved in circles. The heavens appeared to be rolling round the earth, and circular motion seemed one of the fundamental principles of the universe. Not even Copernicus dared to venture beyond that, for he also described the movement of the planets and the stars in terms of circles. Kepler succeeded in breaking away from this ancient belief.

His achievement was not unlike that of Einstein in our own day. Einstein succeeded in imagining that space, which had for thousands of years been supposed to be 'straight', or Euclidian, was in fact 'bent', or non-Euclidian; and proved it. Both of these men, whose scientific achievements and characters have certain re-

semblances, were natives of South Germany. They had tremendous scientific imaginations, and combined supreme achievements with modesty. They lived through wars and revolutions and became wanderers, yet were not distracted from accomplishing prodigious works. Both of them conceived their most brilliant ideas while they were in Prague. When Kepler was driven from his last permanent residence, he first went to Ulm. There in 1627 he published the Rudolphine Tables. Two and a half centuries later, Einstein was born at Ulm.

Kepler was born on 27 December 1571 in the small city of Weil near Stuttgart in Würtemberg. He came of a family which had belonged to the nobility, but had lost its property and become craftsmen. His grandfather was a successful man, who became mayor of Weil. His father Heinrich was a soldier-of-fortune, and his mother Katharina was the daughter of the inn-keeper in a neighbouring village.

At the age of twenty-four Kepler made objective notes about the characters of his ancestors, in order to compare them with what the stars foretold from the dates of their births, according to the principles of astrology. His grandfather was arrogant, impetuous and sensual, and his grandmother religious but apt to tell lies. His father was violent and immoral, and his mother dark, wiry, determined and quarrelsome. He related these qualities to the position of the stars at the times of their births.

Kepler was his parents' first-born. He was a weakly seven-months' child, and grew up small and slight in figure. He had poor eyesight, which disqualified him for observational astronomy, especially when this was

done with the naked eye, before the invention of the telescope. He became a graceful man, with dark hair and black eyes, evidently taking after his mother.

The Kepler parents were unable to provide a proper home for Johannes and their other children. Katharina Kepler was opinionated and argumentative, and deeply interested in herbs and magic. Ultimately she was accused of being a witch and tried for witchcraft, being saved from torture and the stake only through six years of persistent legal defence by her son, who by then had achieved world fame.

Heinrich Kepler had soon found her too much for him. Though a Protestant, he fled to the Netherlands to enlist in the Catholic army of the Duke of Alva, engaged in suppressing the Dutch, and preparing to invade England. This, however, did not enable him to evade his wife. She packed up her home, deposited her son Johannes with his grandparents, and routed out her husband in Holland.

Johannes caught smallpox and nearly died. Presently his parents returned, but before long his father was off again, to fight in Italy. Nearly everything in Kepler's infancy was against him, except the system of education in Würtemberg. Under the influence of the Reformation efficient schools had been founded, as instruments to establish Protestant beliefs, and the university at Tübingen had been made one of the leading centres of Protestant scholarship.

Young Johannes was at first sent to the kind of school suitable for a future craftsman, where the instruction was in German. The good teachers in this school noted his mental quickness and advised that he should be sent to

one of the Latin or grammar schools. He was transferred at the age of seven. It seems that the Würtemberg teachers were practising what we should call 'seven plus' transfers. Kepler began to acquire his notable mastering of Latin, but did not complete the course quickly, as he was taken from school from time to time to work in the fields. It became obvious that he was not physically strong enough for manual work, so his teachers recommended that he should study to qualify as a Protestant pastor. This agreed with Kepler's own desires, for he had a religious disposition, and no doubt sought refuge in religion from the misery of his home life. Religion remained for him a most serious concern, about which he was flexible, but never compromised on principles, in spite of loss and danger.

In this period of enthusiasm, the path for a capable youth who wished to enter the ministry was smooth. Free places and scholarships were provided. Without expense to his family Kepler attended a residential seminary, and subsequently graduated in philosophy, at Tübingen.

Kepler noted his own character with the same objective eye as he had those of his parents. He says he failed to control his tongue, and was inclined to be obsequious, arousing hostility among the other youths by telling tales on them when pressed. He could not bear not to have the good opinion of his superiors. His tendency was always towards moderation, which made him unpopular with both extremes. In religion he could not believe that God would damn heathens who do not believe in Christ. In politics he desired to promote peace

rather than strife, and to emphasize those things on which people can agree rather than those on which they differ. He was in favour of peace between Lutherans and Calvinists, and a fair deal for Catholics. So to the end of his days, though he knew many people, he had very few firm friends.

At Tübingen Kepler had first-rate teachers. The professor of Greek, Crusius, was one of the best Greek scholars in Europe. He later tried to persuade Kepler to collaborate with him in editing Homer. The professor of mathematics and astronomy was Mästlin, one of the leading contemporary astronomers. In his university lectures, Mästlin as a good Lutheran taught the official view that the sun went round the earth, but privately he explained the Copernican system to Kepler.

While Kepler received excellent instruction in astronomy, and much is known about the development of his mind and interests, there is no record of how he received his chief inspiration. This was his Platonic philosophy, in which the material world is regarded as a realization of ideas, and in particular of geometrical ideas. According to this philosophy God had made the universe a harmonious creation by designing it on the principles of mathematical proportion.

In his later work on the *Harmony of the World* Kepler said that each planet emitted a particular melody, which could be heard by the intellect if not by the ear. He even wrote down melodies in musical notation, which were supposed to represent the musical harmonies emitted by the various planets.

Kepler's notions, his gift for computation, and perhaps

his mother's influence made him a skilful astrologer. He acquired prestige among his fellow students by foretelling events. In spite of his success as an astrologer, he had not yet any idea of becoming an astronomer. He still intended to be a pastor. Then, in 1594, the Protestant region of Styria in Lower Austria applied to Tübingen for a teacher of mathematics in their college at Graz. The university recommended Kepler, who had not specialized in mathematics and was not yet conscious of his scientific genius. He accepted the post only on the condition that it would not prejudice his prospects of later becoming a pastor.

The college was a vigorous institution, which had been founded twenty years before in opposition to the Jesuit schools. Like the school where he had himself been educated, the college was regarded as a weapon in the great struggle against Catholicism, besides being a school in the ordinary sense.

In addition to his teaching post Kepler was appointed 'district mathematician'. He had to compile calendars and act as the local astrologer, foretelling weather and events. Astrology was regarded as a realistic science, giving information of a highly practical character, telling farmers when to plant seeds and mate their cattle, and businessmen the days on which their deals would be lucky.

The part of Kepler's work most esteemed during his lifetime, by school-fellows, aldermen and emperors, was his astrology. It was the main source of his income. As he grew older and penetrated more deeply into science he became more and more critical of it. He described it

as an illegitimate and disreputable daughter of astronomy, whose earnings nevertheless enabled her respectable mother to live. He used it as a means for clothing the expression of opinions which would otherwise have been dangerous. Nevertheless, Kepler believed it contained some residue of truth, resting on the universal connection between all things in nature and man.

Kepler was not a good teacher. His mind seethed with ideas, and he could not prevent himself from pursuing new thoughts as they occurred, even in the middle of a class. He tried to seize and express them immediately, in a rush of words which were unclear to himself and unintelligible to his pupils, who soon stopped attending his classes. Consequently, he had a good deal of spare time. He used this for composing his first masterpiece.

He had learned the Copernican theory from Mästlin, and, as is the way with youth, he took up the new theory with more outspoken enthusiasm than his master. One of the advantages of the Copernican theory was that it enabled the relative distances between the planets and the sun to be calculated. With his profound Neo-Platonic convictions Kepler was certain that these distances and other mathematical features of the solar system arose out of an inner harmony. He searched zealously for the reasons for three things in particular: 'the number, the size, and the motion of the heavenly bodies', and 'why they were as they were and not otherwise'.

He imagined many kinds of connections between the various data, and worked out their consequences, but they led nowhere. Finally, to his amazement and intense excitement, he did discover a series of mathematical

relations concerning the distances of the planets from the sun, which seemed to him to contain the very secret of the structure of the universe. He showed that the orbits of the planets could be fitted into a series of regular geometrical figures, rather like a series of Chinese boxes, each of which contains a smaller one within itself. These were the cube, the tetrahedron, and the three other regular solid figures discovered by the Greeks, to which Plato had assigned a fundamental role in his picture of the structure of the universe.

Kepler found that if a cube were inscribed in the sphere containing Saturn's orbit, then the sphere of Jupiter's orbit could be inscribed within this cube. If a tetrahedron were inscribed in the sphere of Jupiter's orbit, then the sphere of Mars's orbit could be inscribed in this tetrahedron; and so on. The agreement was not very exact, and, up to the present, has not been found to have any significance, though modern astronomers have been much concerned with the explanation of the particular sizes and distances of the planets.

Kepler described his theory in his *Mystery of the Universe*, published in 1596. He sent copies of the book to Mästlin, Tycho Brahe, Galileo and others. His mathematical ingenuity and capacity for computation made a deep impression. As has already been mentioned, it awakened Tycho's interest in Kepler. Galileo acknowledged his copy with congratulations on his courage in openly supporting the Copernican theory, which circumstances, he said, had prevented him from doing himself. He made no technical criticism of the book. Kepler wrote again, urging him to support Copernicus

openly, and saying that he would welcome intelligent criticism, however sharp, far more than enthusiastic approval from the ignorant.

Kepler's mode of thought was unsympathetic to Galileo, who liked to be transparently clear, and described his discoveries with wonderful acuteness; he was a great popularizer as well as discoverer. Kepler, in contrast, was preoccupied with trying to divine the inner causes of things. He probed the depths of the unconscious and brought up an extraordinary mixture of strange fancies and great discoveries. He dreamt about travelling in space, and was one of the inventors of what is now called science fiction.

The followers of Galileo, who were more rationalistic, were inclined to feel that somehow Kepler's discoveries were unfair. They appeared like miraculous scientific rabbits out of the hat. Today, when scientists no longer picture the atom as working like a tiny machine, every part of which they can see perfectly clearly, the methods they use for trying to discover the secrets of nature are becoming more like those of Kepler than Galileo.

The great importance of unconscious thinking in the process of discovery is now better understood, and much in Kepler which seemed to be gibberish is now seen to have meaning. We are accustomed to thinking of the solar system as an enormous machine in which big material bodies revolve round the sun, like fly-wheels on a factory engine. Kepler's original inspiration was quite different from this, though indirectly it led him to our picture of the solar system as a big machine.

In the depths of his mind he conceived the universe

not as a machine but as a kind of super musical instrument, whose parts had been proportioned by God to cause it to emit divine harmonies as it moved. Impelled by this idea he discovered new facts, which he gradually saw could be explained on mechanical lines, but he was not inspired by mechanical ideas in the first place.

Kepler did not believe in the significance of mere coincidences between numbers. He thought he was discovering something infinitely more real and important, the geometric skeleton and foundation on which God had constructed existence. He said that geometry is a reflection of the mind of God, and the fact that man has a knowledge of geometry is one of the reasons why he has been called an image of God. He believed that God copied Himself in making the world, and that it was because of this that the study of nature gave insight into His mind. He regarded the growth of crystals, the blossoming of plants and man's own creative activity as the imitation of God Himself at play. He said as God played, so He taught His image nature to play the very same game that He had played while creating nature. Kepler believed that God had created nature purely at random, as a playful activity, and geometry symbolized the essence of nature and the elegance of God; it was the divine style in expression. Kepler developed these conceptions through his various works. He conceived the sphere as the symbol of the Holy Trinity, the centre representing God. The surface, which was described by a radius from the centre, represented the Son, and the volume the Holy Ghost. When he saw children blowing soap-bubbles, he thought of them as imitating the

role of the Creator, by blowing up the spherical universe from the original primeval drop.

The modern cosmologist is reminded of the theories of Lemaître on the expansion of the universe from an original primeval atom. Kepler's scientific insight penetrated far.

While Tycho Brahe immediately appreciated the intellectual quality of Kepler's *Mystery of the Universe*, he also reacted to it as a great organizer of research. He at once thought of securing Kepler as one of his assistants, and invited him to join him.

More than a year passed before Kepler first visited Tycho, as he was more concerned in settling down in his own Protestant community. He desired to marry the twenty-two-year-old Barbara Müller, the daughter of a rich miller. In spite of her age, she was already twice a widow, her former husbands having been middle-aged men with money or position. The miller did not welcome the prospect of a son-in-law who was a poor teacher, however intellectually distinguished. He insisted on Kepler producing evidence of gentlemanly descent, and he gave his daughter a much smaller dowry than was expected.

Kepler was at first happy in his marriage, but soon began to look at it with his objective astrological eye. He compared his wife's character with what the stars portended. Though she was praised by everyone for her virtue, modesty and humility, she was simple-minded and fat. She had married middle-aged men against her will. She was unable to manage ordinary affairs with competence, and had allowed herself to be cheated of her full fortune.

Their first child was born in 1598, but died after a few weeks; a second was born in the following year and died even sooner. Altogether, Kepler had six children by his first wife, only two of whom grew to maturity. He was now committed to Protestant Styria and Graz, through his post and his family connections and troubles.

At this time, the new young ruler of Austria, the Archduke Ferdinand, under the influence of the Jesuits, announced his intention of converting the Protestant regions of his dominions to Catholicism. Pressure was put on the Protestants at Graz, who resisted, and severe measures were soon taken against them. The Protestant preachers and teachers were ordered to leave the city within twenty-four hours. Kepler left with the rest, and went to Hungary.

He was loth to leave Graz, especially because of his wife's as yet unreceived fortune. Kepler had a middle-class preoccupation with money which diminished his dignity as a man. He petitioned to remain in Graz on the ground that his work as district mathematician was of a neutral character. He was the only expelled Protestant who was given permission to return. This may have been due to the influence of the Chancellor of Bavaria, von Hohenburg, who was an able Catholic statesman and friend of the Jesuits, and deeply interested in astronomy. He had already been in touch with Kepler on scientific questions. The Catholic scientists no doubt hoped to convert Kepler to their beliefs.

Kepler was in favour of independence of religious opinions, and of peace and moderation in propagating them. He disapproved of the aggressive young Protestant

pastors in Styria, who wanted to rule as well as preach. He said that in such dangerous places it was necessary to behave with the cleverness of the serpent, in order to preserve one's own conscience, and at the same time not upset the Catholic rulers.

The persecution launched by Ferdinand was part of the developing Counter-Reformation, the movement led by the Jesuits to recover for the Catholic Church the ground lost through the Reformation. Kepler succeeded in surviving it, and even in keeping on good terms with its leaders, without compromising his opinions. He was enabled to do this by his ability and honesty, but also by an innate lack of dignity in his character. Inwardly he felt inadequate. He compared himself with a pet dog which wants to be liked by its master, and will run any errand and put up with any reproof from him, but barks on the approach of others. He felt unpopular with people in general, though he was liked by his masters. His honesty about himself helped him to mitigate the effects of his natural weaknesses. He used his intelligence to remedy them, with considerable success.

Kepler's position in Graz, as an isolated Protestant with no pupils, became increasingly uncomfortable. He thought again of Tycho Brahe's invitation to go to Prague. His friend Baron Hoffmann, a member of the Styrian Government and of Emperor Rudolph's court, offered to take him to Prague and introduce him to Tycho.

Kepler arrived in Prague in January 1600. In the meantime, Tycho had repeated his invitation in a letter that passed Kepler on the way, asking him to come of his own

free will and not as one driven by misfortune. When Tycho, who was at Benatky, heard of Kepler's arrival in Prague he was overjoyed, and immediately sent a message that he would be received not as a guest, but as a very welcome friend and collaborator.

When the two men met, Tycho was fifty-three, with his life-work accomplished, and faced with the task of harvesting its fruits. He had revolutionized the observations of the planets and stars, and had done virtually all that an observer of genius could do. He now needed a genius in theory to work out the meaning of his observations. He hoped that this would prove that his System of the World, and not Copernicus's, was the correct one.

The twenty-eight-year-old Kepler stood before him, confident that he was on the track of the Mystery of the Universe. He believed that the reason why the solar system did not quite fit his box of geometrical tricks was because the astronomical observations were not sufficiently accurate. He hoped that the more exact observations of Tycho would show that the fit was perfect. He arrived in Prague with the ambition of securing these more exact observations from Tycho, but he found Tycho's regime disconcerting. Tycho was accustomed to wealth and authority, whereas Kepler was a poor teacher of middle-class origin, who had married for money, and was inwardly conscious of his dog-like nature as well as his sublime genius.

He had difficulty in behaving with the independence due to his genius, and in holding his own in the presence of a famous and wealthy aristocrat, at the same time

humouring him sufficiently to get the unique observations upon which the proof of his own discovery rested.

As Kepler wrote: 'Tycho possesses the best observations and thus the material for the erection of a new structure; he has also workers and everything else that could be desired. He lacks only the architect who uses all this according to his own plan. For, even though he too possesses a rather happy talent and genuine architectural ability, still he was hindered by the diversity of the phenomena as well as by the fact that the truth lies hidden exceedingly deep within them. Now old age creeps upon him, weakening his intellect and all his faculties, or will so weaken them after a few years, that it will be difficult for him to accomplish everything by himself.'

Brahe, aware of the value of the observations on which he had spent his genius, fortune and life, was not inclined to disclose them easily. Kepler found that he had to sit out interminable meals conducted in baronial fashion, in order to collect a few more items of vital astronomical observation at the end. He calculated that at this rate it would take two years to get what he wanted from Tycho. He thought that if he stayed in Prague for that time, the situation in Styria might become easier. He hated the idea of abandoning his wife's fortune, with its promise of financial independence.

He prepared an extraordinary memorandum defining the conditions upon which he was prepared to collaborate with Tycho. He said that the confusion of Tycho's household got on his nerves and caused him to lose his temper in intellectual argument. This made it impossible for him to live in it. This memorandum was unintentionally put

TYCHO BRAHE

JOHANNES KEPLER

into Tycho's hands. Tycho was justifiably annoyed with Kepler's remarks, and indicated that he desired a written apology. Kepler became very ashamed of himself after thinking over his behaviour, and sent a characteristically honest apology, which Brahe, with his practical sense, accepted.

Kepler now became very anxious to return to his family in Styria. Brahe said he would intercede with the emperor that Kepler should be given leave to come to Prague for two years to assist in the publication of Brahe's work. In order to preserve his independence, Kepler stipulated that he was to retain his position and salary as District Mathematician at Graz.

Kepler started on his homeward journey with Rosencrantz, the Danish nobleman and relative of Brahe. When he arrived home he found that the Graz authorities were not impressed by the imperial proposals made in Prague. They said he would be more useful to them if he knew medicine, and proposed to send him to Italy to study it. In those times, astrology and medicine were closely related. Kepler considered the suggestion seriously, and conceived the alternative plan of becoming Mathematician to Archduke Ferdinand. He dedicated an essay to him, as a qualification for the appointment. In it he proposed to abolish the system of uniform circular motions used to explain the complicated movements of the moon, and substitute for it a non-uniform motion. He justified this on the ground that nature prefers simplicity. It was the beginning of the break-away from the ancient ideas. He suggested that there is a force in the earth which causes the moon to move. The further

the moon was from the earth, the weaker the force would be, and therefore the moon would move less quickly. This was the start of the physical explanation of the theory of gravitation.

The brilliant essay was graciously received, but Ferdinand did not give Kepler the desired appointment. Shortly afterwards, Ferdinand started a general expulsion of non-Catholics from Graz. Kepler refused to evade it by changing his faith. He was finally dismissed from his post, lost his salary, and was banished. He wrote to Brahe about his plight, who replied immediately. Tycho reported that the emperor had only just then indicated by a nod his consent to the proposed arrangements for Kepler. He enthusiastically advised him to come to Prague without delay.

Kepler left Graz at last, and said that he would not have thought it could have been so sweet to abandon home and country for the sake of religion. He still tried to secure a chair at Tübingen, so that he could return to his native land, but the Lutheran faculty refused to overlook his theological heterodoxy. He had no alternative to Prague. In spite of his achievements, Kepler never secured a university chair.

He arrived in Prague in the autumn of 1600. He was depressed and ill, and his wife was unhappy in her isolation among foreigners, and loss of means. She was deeply shocked by the Prague inflation, prices being four times higher than in Graz. Kepler found himself in complete dependence on Brahe, in the very position he had been at such pains to avoid. Brahe had been having his own difficulties, and his temper had become still

more capricious. Nevertheless, he proved to be the only one who helped Kepler after his banishment from Graz.

He personally introduced Kepler to the emperor, who commissioned him to collaborate with Brahe in the compilation of the new tables of the planets: the Rudolphine Tables. A few weeks later Brahe became fatally ill. On his deathbed he bequeathed his incomparable observations to Kepler, asking him to work them out according to the Tychonic system of the world.

Kepler regarded his inheritance of Brahe's intellectual estate as an act of God. Two days after Brahe's death, the emperor appointed Kepler to succeed him as Imperial Mathematician. Kepler now found himself at the centre of the world-stage, in an environment which had breadth and perspective in keeping with the magnitude of his genius.

The atmosphere in Rudolph's Prague was, like the emperor himself, strange and magnificent, but the young Catholic politicians and soldiers chafed under his religious and political indifference. They wrested his individual kingdoms from him one by one, and finally, in 1611, his brother Matthias seized the Bohemian crown. Rudolph did not leave Prague, but died shortly afterwards, in 1612.

Kepler lived in Prague from 1600 until 1612, and did not leave until after the death of his patron. His official salary was only one-sixth of that of Brahe, and was as irregularly paid. He tried to recover his arrears by mercenary nagging. Nevertheless, the cultivated, slightly mad, and unstable atmosphere of the imperial city

provided a splendid soil for the stimulation of his genius. Its unconventionality suited his original imagination. There was no need to repress odd new ideas where oddness was the rule.

Tycho had asked Kepler on his first visit to Prague to investigate the movements of the planet Mars. He assigned this task to him because it was the most important. The deviation of Mars from movement in a perfect circle is very pronounced and offered the most promising way of discovering the nature of the irregularity of the planetary motions. Brahe had made a large collection of exact observations of the planet, so Kepler made a thorough analysis of them. He succeeded in reducing the complications of the problem by a brilliant technical device.

The greatest difficulty in explaining the irregularities in the movement of a planet arises from the fact that observations of it are made from the earth, which itself has irregularities in its motion. The two sets of irregularities mixed up together seemed an inextricable muddle, and had defeated everyone. Kepler discovered a very ingenious way in which the effects of the earth's irregularities could be eliminated from the calculations, thus enormously simplifying the problem. He then calculated where the planet would be on no less than seventy various suppositions, and compared the results with Tycho's observations. At last he found a system which gave the positions of the planet to within nearly a tenth of a degree of Tycho's observations.

The temptation to assume that the slight difference was due to the inevitable inaccuracies of observation was

enormous, but Kepler knew that Tycho's observations were more accurate than this would imply. With his supreme genius, he resisted the temptation, just as he resisted religious surrender in the desperately dangerous conditions of the Counter-Reformation.

'Since God has given us a most careful observer in Tycho Brahe, whose observations show an error of 8 minutes in the calculation . . . we should recognize this gift of God and make use of it. . . . If I could have treated 8 minutes of longitude as negligible I would have corrected the hypothesis sufficiently. But as they could not be neglected, these 8 minutes alone have led the way towards the complete reformation of astronomy.'

He continued once more with trying various combinations of circular motion, but none of them fitted, so at last he gave them up. Kepler now tried various oval curves, starting with egg-shaped ovals bigger at one end than the other. These did not fit, and at last he tried the ellipse, the simplest form of oval curve. He found that it fitted very well if the sun were placed, not in the centre of the ellipse, but at one of its foci.

Thus he completed his break with the past, and delivered one of the biggest blows to Aristotelianism, which had laid down that motion in circles was a fundamental principle of nature.

While the discovery of the elliptic shape of the orbit was a major break with the past, the discovery that the planet revolved with the sun exactly at one of the foci was not less important. Copernicus's theory that the planets revolved round the sun in circles was only approximate. According to it, the planets revolved around the

centre of a circle. This centre did not exactly coincide with the sun, and was in fact merely a point in space.

When Kepler found that the sun was precisely at one of the foci, he substituted a physical body for the mathematical points of both Ptolemy and Copernicus. He transformed astronomy from a science of formal mathematical description into a science of physical bodies. He began to consider the sun as the physical cause of the revolution of the planets around it. He began to imagine forces from it, which whirled the planets round. Inspired by this notion, he guessed that the sun must be rotating, before this had been actually discovered from sunspots. Descartes probably got his idea of vortices from him.

Kepler was greatly assisted in his transformation of astronomy from mere mathematical description into a physical science, in which movements were explained as a result of physical forces, by his reading of William Gilbert's book on *The Magnet*, which was published in 1600. Gilbert's idea of magnetic forces in space gave Kepler a more concrete notion of force. Without Gilbert, Kepler would probably not have succeeded in this part of his work, for his deepest insight was in geometrical and numerical relations, and not into how things work, in spite of his great contribution in this direction. These were forced on him as a result of his prior discoveries inspired by his Neo-Platonic notions, which were more akin to music and art than machinery.

Kepler was not content with the magnificent discovery of the elliptical motion of the planets. A planet in an elliptical orbit will vary in its distance from the sun. He compared the speed with which the planet moved in

relation to its distance. He found that it moved slowly when it was far away, and faster when it was near to the sun. By a mixture of perseverance and inspiration, he found that the line joining the sun to the planet always sweeps out equal areas in equal times. He was guided in this marvellous discovery more by his fundamental belief in the mathematical harmonies underlying nature than in the logic of his mathematics.

In his book on the *New Astronomy*, published in 1609 and dedicated to Rudolph, containing his first two laws of planetary motion, Kepler decorated the diagram illustrating his discovery with a little drawing of Victory riding in a chariot over the clouds.

In the year after Kepler published his *New Astronomy*, Galileo announced his startling telescopic discoveries. Kepler saluted them with intense enthusiasm, and immediately applied himself to the theory of geometrical optics. At a stroke he laid the foundations of the subject, improving the theory of refraction and lenses, and presenting it in substantially the same form as is now taught in schools. He personally invented the astronomical telescope. This had a bigger magnification than the Galilean telescope, which was on the opera-glass principle and gave upright images. The images in Kepler's telescope were large but upside-down, which did not matter with astronomical objects. Unlike Galileo he was not particularly talented as an observer and experimenter, and he did not make a specimen of his telescope himself.

Kepler was doing this brilliant work during the turmoil leading to Rudolph's abdication. Nevertheless, when Galileo left Padua for Florence and recommended Kepler

as his successor, Kepler did not accept his proposal. He was preoccupied with the increasing illness of his wife. She was never happy in Prague, and declined into melancholia and epilepsy. He sought for a post nearer her native place, where she might be happier, and he persuaded the authorities of Upper Austria, situated at Linz, to appoint him as teacher and district mathematician. Before the negotiations were completed his wife died, and this was followed soon after by the abdication and death of Rudolph. Kepler nevertheless decided to go to Linz. He thought that the provincial post would give him more quiet for his researches.

He was allowed to retain his appointment as Imperial Mathematician, which was made more of a consultative nature, and his salary was reduced. The authorities at Linz, however, paid him more regularly. He was materially quite comfortable there, but he presently found the lower status of his Linz post and the narrower provincial life frustrating after the imperial atmosphere of Prague.

He decided to marry again, to have a spouse who would look after him and his household. He discussed in detail with his friends the desirable qualifications. He was himself forty-one years old. Should she be a widow or a girl? Should she have a fortune? If so, would she be extravagant? If she was poor and had many relatives, would he be called upon to support them? Would a stout wife be suitable for a thin man? What religious views should she have in the light of his unorthodoxy?

Kepler tried to solve the problem of his second marriage by the same methods with which he attacked the mystery of the universe. After exhaustive inquiries he drew up a

short list of eleven candidates, and then started on a systematic analysis of their qualifications. By the time that he had worked through the first four cases, he had become so worried and perplexed that he nearly had a nervous breakdown. The problem was more intricate than the mystery of the universe. He gave up, and decided to settle on the fifth. She was Susanna Reutinger, a twenty-four-year-old orphan girl, who had been brought up in the noble family of the von Starhembergs.

Kepler was delighted with her. She was industrious, and had been taught to be willing to learn. Public opinion considered she was too young for him, yet the marriage was more successful than his first, and reasonably happy. She bore him seven children; as in his first marriage, few survived. Among his surviving children, his son Ludwig became a physician who exploited his father's fame, and solicited Galileo to secure money for him from the Medici. His daughters Susanna and Cordula grew up and married, and had descendants.

During his years at Linz, Kepler worked on at the computation of the Rudolphine Tables. The most famous of his works published during this period was his *Harmony of the World*, which was the final expression of his quest for the secret of the universe. Pursuing his Neo-Platonic ideas and the principles of his *Mystery of the Universe*, he extended his attempts to discover harmonious proportions in the geometrical and numerical features of the universe.

He made a thorough study of the theory of music, and he read the treatise on this subject by Galileo's father with as much attention as the works of Galileo himself

He explored the mathematics of the Greeks and Alexandrians, and scholastic philosophy, as well as making detailed calculations about proportions on the solar system. Among these, he investigated the relations between the size of orbit and time of revolution of planets, and to his amazement discovered that the squares of the times of revolution of any two planets about the sun are proportional to the cubes of their mean distances from the sun.

It is difficult to find words to express the brilliance of the discovery of such a complicated mathematical relation from the relatively crude observational data at his disposal. He had only the observations of pre-telescopic, naked-eye astronomy to work with. It was miraculous to find such a precise and subtle relation among such material.

He made the great discovery of the third, and most important, law of planetary motion on 15 May 1618. It was from this law that Newton derived the theory of gravitation.

Kepler himself thought that his discovery was pretty wonderful. A few days after making it, he wrote: '. . . I give myself up to sacred frenzy. I scornfully defy mortals with the open avowal: I have plundered the golden vessels of the Egyptians to furnish a sacred tabernacle with them for my God, far from the borders of Egypt. If you forgive me, I shall be pleased. If you are angry with me, I shall bear it. Well, then, I cast the die and write a book for the present, or for posterity. It is all the same to me. It may wait a hundred years for its reader, as God too has waited six thousand years for a spectator.' The last sentence is a striking example of Kepler's Neo-Platonic thinking.

While the book was in preparation, the Elector Palatine, James I's son-in-law, was proclaimed King of Bohemia, after the rebellious Bohemians had thrown objectionable ministers out of a window of the Prague Castle overlooking a steep cliff. Kepler had long admired James I as a theologian, and the apparent rise in political importance of his son-in-law reinforced his decision to dedicate the work to him. James appreciated the honour, and sent his ambassador Sir Henry Wotton to call on him, and offer him a post of honour at the British Court. Kepler did not accept it, writing: 'I go over the sea, whither Wotton invites me? I a German? I who love the continent and shrink back from the narrow confines of an island, whose dangers I sense beforehand?'

After the decisive defeat of Frederick at Prague in 1620, the dedication of the *Harmony of the World* to James raised a delicate problem, and a number of copies of the book were issued without it. In the executions that followed in 1621, many of Kepler's old friends in Prague lost their lives. Nevertheless, Ferdinand, who had succeeded Matthias as Emperor Ferdinand II in 1619, had confirmed Kepler's position as Imperial Mathematician; he survived once more.

In reply to his persistent efforts to collect his 12,000 thalers arrears of imperial salary, Kepler was told that the responsibility of finding the money had been transferred to Wallenstein, the Imperial General. In 1608 Kepler had been visited by an eminent doctor who had asked him to foretell from the stars the future of a young nobleman who was unwilling to give his name. Kepler, who had a shrewd idea of who the gentleman was,

compiled the document, and then, in 1624, sixteen years later, was astonished to receive it back from Wallenstein. In it, Kepler had given a remarkable description of Wallenstein's personality.

The famous Captain-General now asked Kepler for precise information on his future. He wanted to know whether he would die of a stroke, be successful in military campaigns, and who his enemies would be. Kepler explained that he did not believe that answers to such questions could be derived solely from the stars; personal temperaments and political factors had also to be taken into consideration. He said he would, however, tell him what calculations based solely on the stars would indicate. He said that he would have friction with the young King Ferdinand of Bohemia, and he forecast terrible events ten years hence, in March 1634.

When the fatal year came, four years after Kepler's own death in 1630, Wallenstein was murdered, on 25 February.

Kepler's negotiations with Wallenstein led to his moving to Sagan, in Wallenstein's dukedom in North Germany. He went there in 1628, but Wallenstein still didn't find the 12,000 thalers, owing to the expenses of his military campaigns.

At Sagan Kepler found it difficult to adapt himself to the North Germans. He was disturbed by religious strife in the city, and especially by the activities of the redoubtable King Gustavus Adolphus of Sweden, who was threatening Germany. Kepler took refuge from the uncertainties of the times in intense intellectual work and calculations.

Only Wallenstein correctly assessed the threat of Gustavus Adolphus, but at this moment the emperor chose to dismiss him. He perhaps feared that Wallenstein would seize the imperial crown, and he wished to ensure that his young son Ferdinand, King of Bohemia and Hungary, should succeed him. He called a meeting of the imperial electors at Regensburg, to confirm the succession. In due course his son became Emperor Ferdinand III.

Kepler set off from Sagan to Regensburg to look after his interests. He wanted to inquire about property at Linz, and see what more he could do about his arrears of imperial salary

He arrived at Regensburg after a tiring journey on horseback, and fell ill. He did not at first think it was serious, but acute fever and delirium developed. He died on 15 November 1630. Many of his friends, and important personages who had been in the city for the imperial election, attended his funeral. He was buried in the Protestant cemetery of St. Peter, but all trace of his tomb disappeared in the destruction of Regensburg four years later, in the course of the Thirty Years' War.

Kepler's achievements were astounding, not only in their importance, but in the conditions under which they were made. There were not only his planetary laws, which stand among the greatest of human discoveries, but a mass of other work. He suggested that the tides are due to physical forces emanating from the moon. He recognized the corona as part of the sun's atmosphere, and suggested that comets' tails pointed away from the sun because they were repelled by a force from it.

He was a gifted pure mathematician. A consideration

of how a curved volume, like that of a barrel, could be calculated, led him along the path towards the invention of the calculus. He was among the first to welcome Napier's invention of logarithms. As a prodigious computer himself, who had spent much of his life in lengthy arithmetical calculations, no one was better qualified to appreciate the invention, which he did with characteristic generosity in the dedication to Napier of a little book on logarithms. This was published in 1620, Kepler not having heard that Napier had died three years before.

Kepler's life provides a wonderful example of what imagination and persistence can achieve in science, and what can be done even under the most disturbing conditions of mental, religious and political conflict.

From the depth of his soul he wrote: 'If the mind has prepared itself to contemplate what God has created, then it is also prepared to do what God has commanded. Should this state of mind have been achieved by all, then there would be nothing further to desire for mankind than that all people of the whole globe should live together in one city, and, removed from all strife, take pleasure in each other already in this world, as we hope to do in the next.'

REFERENCES

Kepler, by Max Caspar, translated by C. Doris Hellman. Abelard-Schuman.

Johannes Kepler: Life and Letters, by Carola Baumgardt, with an introduction by A. Einstein. Philosophical Library, New York.

III

EDMOND HALLEY

1656–1742

EDMOND HALLEY was born only twenty-six years after the death of Kepler, yet he belongs to another age. While Kepler lived in an atmosphere of magic and astrology, probing the unconscious mind of man and bringing up astounding discoveries from the depths, Halley was already a man of the Age of Reason, in which things were bright and clear, or could be made so by the exercise of the understanding.

If Kepler could meet astronomers today, many of his ideas would seem strange, but Halley would be perfectly at home in outlook and mode of thinking. His mind is reflected in his attitude to astrology. While Kepler never completely extricated himself, Halley from the beginning of his astronomical life had no use for it. John Aubrey tried to interest him in it, and Halley wrote to him in 1679: 'As to the advice you give me, to study astrology, I profess it seems a very ill time for it, when the arch-conjurer Gadbury is in some prospect of being hanged for it. . . .'

The difference in atmosphere between Halley's England and Kepler's Germany was very big. No doubt the clarity and scepticism of the English astronomer arose from the new motives for astronomical research, provided by the

needs of the new society in which he lived, which was based on ocean navigation and trade.

Kepler lived in a society still dominated by feudalism, whose interest in astronomy arose from other motives, going back to the ancient need for determining the seasons, and regulating the cultivation of plant and animal life. He was involved in the residue of magical ideas from primitive agricultural society, whereas the mind of Halley had been clarified by the gales of new knowledge from the ocean navigations and the New World.

Halley is universally famous for his prediction of the date when the comet named after him would next be visible. It was the first great prediction based on Newton's theory of gravitation, and had immense influence in convincing both astronomers and public that the wonderful new science was really true.

Halley's most famous achievement was very important, as well as spectacular. It was, however, only the best-known incident in an immense range of creative work. Besides his astronomical investigations, he invented several new sciences, including geophysics, or the physics of the earth as a whole; and the mathematical theory of life insurance. The former has led to such developments as the International Geophysical Year, and the latter to modern insurance and the science of population, which have contributed so much to the conception of social planning and the welfare state.

Halley's success in starting such fundamental developments in two apparently very different fields arose from the application of the same kind of talent in both cases.

He had a particular genius for analysing masses of facts that cannot be summarized by any simple formula like the law of gravitation, and must be handled by other methods.

The author of the account of Halley in the proceedings of the French Academy of Sciences after his death wrote that while he had thought that the whole subject would have been covered by the story of an astronomer, a physicist, a scholar and a philosopher, he had found that, as he proceeded, he gradually became aware, to his surprise, that he was composing in addition 'the history of an excellent mariner, an illustrious traveller, an able engineer, and almost a statesman . . .' As Augustus de Morgan remarked, 'such varied knowledge, so deep in all its parts, such universal energy, so equally distributed through a long life—have hardly a parallel.'

Besides being a great astronomer, Halley was the most versatile of English scientists. His natural gifts were so great that he stepped from boyhood into a leading position in life.

Halley was a Londoner. His grandfather was a wine-seller who owned inns. His father was a rich soap-boiler in Winchester Street, who had a house at Haggerston in Shoreditch, which at that time was a suburb where city merchants had country houses. He married Anne Robinson, and their son Edmond was born at Haggerston on 29 October 1656.

England was then being ruled by Cromwell, and the Halley family shared in the wealth and energy which was created and released in that period. Halley senior owned many houses in the City. He suffered heavy losses

through the Great Fire of 1666, when Edmond was ten years old, but even after that he was still well off.

Like other sons of City merchants, Edmond was sent to one of the great Cathedral grammar schools, in his case St. Paul's. By the age of fifteen he had become captain of the school, with a good knowledge of mathematics, Latin, Greek and Hebrew. He had a passionate interest in science, and read and experimented on his own. This does not usually do more than give pleasure and a valuable background of general scientific knowledge, but with Halley it characteristically led at once to original observation. At the age of sixteen he discovered that the direction of the earth's magnetic field at London was changing, before he learned that this was already known.

Halley senior was proud of his brilliant boy. Like many City merchants of the period, he respected intellectual things, and took a sympathetic interest in his son's scientific activities; he enabled him to buy astronomical instruments. Edmond made observations with these from his father's house, and acquired sufficient knowledge of geometry and mechanical skill to make other instruments His father sent him to Queen's College, Oxford, which he entered in 1673, when he was sixteen. The apparatus he brought with him attracted attention, and he made rapid progress in geometry and astronomy.

Again Halley's studies brought him straight to the boundaries of knowledge. At the age of eighteen he gave a conclusive geometrical proof that the planets revolve round the sun at one focus of their elliptic orbits, and not around a point in space, such as the centre of the ellipse, or the other empty focus. He settled the question of

principle that had defeated Copernicus, and which Kepler had not left absolutely clear. He published a paper on the subject in the *Philosophical Transactions* of the Royal Society in 1676, before he was twenty years old.

Having advanced beyond Copernicus and Kepler, the young undergraduate conceived the plan of improving on Tycho Brahe. He had discovered from his observations that the positions of Jupiter and Saturn could not be predicted accurately from the existing tables, and that the necessary corrections could not be made without more accurate observations of the fixed stars.

The irregularities discovered by Halley in the motions of these planets were subsequently demonstrated by Newton to be a consequence of gravitation.

Hampered by the limitations of Brahe's tables, Halley proposed to make a new more exact catalogue of the places of the stars. On inquiry he learned that the famous astronomer Hevelius at Dantzig on the Baltic coast, and John Flamsteed, the first Astronomer Royal, at Greenwich, were already making such catalogues.

Halley now suggested that as they had the northern skies in hand, he should sail to the southern seas and make a catalogue of the stars of the southern skies, which had not yet been done. Such a catalogue, added to those of Hevelius and Flamsteed, would give a picture of the distribution of stars in the whole sky. Halley was penetrating in his usual imaginative way towards the investigation of the sky as a whole, and thus helping to create modern cosmology.

Halley's father enthusiastically supported the scheme. He gave his student son the best possible help by settling

a handsome allowance of £300 a year on him. Halley was therefore able to proceed independently, which made it easier for him to secure influential support. He discussed his project with the astronomer Sir Jonas Moore, Surveyor of Ordnance, and Sir Joseph Williamson, Chief Secretary of State; both were leading members of the Royal Society. They brought it to the notice of Charles II, who recommended it to the East India Company.

Halley had formed the opinion that the island of St. Helena would be the best place for his observations. Berths were provided for him and an assistant friend called Mr. Clerke, on the East India ship *Unity*, and the Governor of the island, Mr. C. Gregory Field, was ordered to find him suitable lodging.

Halley sailed in November 1676, taking with him a sextant of 5½ feet radius with telescopic sights, a 24-foot telescope, a good pendulum clock and other instruments. The voyage of 1,400 miles took three months.

He found the conditions in St. Helena disappointing; the skies were cloudy and the weather wild. The social arrangements were also trying, for the governor turned out to be drunken and gross. He was subsequently replaced by a man of 'sober life and conversation'.

In spite of the difficulties, Halley observed the positions of 341 stars, which, by the methods he used, also involved very heavy computing. He discovered the great star cluster in the constellation of Centaurus, and he noted the increase in the rate of the pendulum as the ship approached the equator, an effect subsequently explained by Newton as due to the extra gravitational attraction owing to the bulge at the equator. Besides eclipses of the sun and moon,

he also observed the first complete transit of the sun's disc by the planet Mercury. This provided the first measurement of the distance of the sun from the earth 'not based on probabilities'. The experience directed Halley's attention to the possibilities of transits by other planets as means for exact measurement of this distance, which is one of the fundamental units of distance in astronomy. He recommended observations of transits of Venus, which would give more accurate results because it approaches closer to the earth.

He arrived back in England in the autumn of 1678, and presented the king with a map of the southern stars. Charles thereupon informed the University of Oxford that he had received an excellent account of his learning, particularly in mathematics and astronomy, as demonstrated by his observations in St. Helena, and ordered that the degree of master of arts should be conferred upon him. Thus Halley received his first degree on his astronomical achievements, without taking any examination.

He had already presented his catalogue of the southern stars to the Royal Society, and on 30 November 1678 he was elected a fellow, being then twenty-two years old. Halley was intimately connected with the Society for the remaining sixty-four years of his life. He was its assistant secretary for fourteen years, and a member of its Council for thirty-six years.

Halley's was the first published star catalogue based on observations made with telescopic sights. Flamsteed, who had not yet quarrelled with Halley, referred to him as the 'southern Tycho', and Halley seemed to have achieved his ambition. His chief genius was not, however, in

observation but in ideas. Inaccuracies and defects in his observations later irritated the precise Flamsteed. Halley had not the passion of a primarily observational astronomer, such as Tycho or Flamsteed, for every minute detail of the design and manipulation of instruments. He was more interested in observations which opened new vistas than in making very exact measurements.

Within a few months of his return from St. Helena he was off abroad again. He desired to meet Hevelius, the successor of Tycho, who had developed the ancient methods of observation with open sights to their highest pitch. He had had a fierce dispute with Robert Hooke on the value of the recently invented telescopic sights. The Royal Society therefore commissioned Halley to discuss and demonstrate telescopic sights with him.

Halley arrived in Dantzig in the spring of 1679, and the stately old gentleman received him 'with great joy and respect; and they fell to observing the same evening'. Hevelius, though he found Halley a charming guest, a most honest man and a sincere lover of truth, remained unconvinced of the superiority of telescopic sights.

Halley now desired to converse with the eminent astronomers and learned men in France and Italy. He left for France in December 1680, accompanied by his old school-friend, the religious writer Robert Nelson, author of a work on feasts and fasts. They had a most unpleasant cross-Channel passage, taking 40 hours from Dover to Calais, 'with wind enough'. On the road from Calais to Paris, however, they saw the great comet of 1680 receding from the sun. Halley had in the previous month seen it approaching the sun.

He had scientific introductions and commissions in Paris. He met J. D. Cassini, the famous astronomer, and spent much time with him observing the great comet, which was the subject of universal interest. Cassini suggested it was the same comet as that described by Tycho Brahe in 1577, and another seen in 1665. Halley wrote to Hooke that it was 'very remarkable that three comets should so exactly trace the same path in the heavens and with the same degrees of velocity'. The problem of comets was vividly impressed in his mind.

In the same letter to Hooke, he sent some observations on the comparison of Paris with London, for size and population. He deduced the size of the population from the numbers of burials, christenings and weddings, and the 'notion occurred whilest' he was writing, 'that it is necessary for each married couple to have four children one with another to keep mankind at a stand.'

Halley spent nearly two years on his European tour. He returned to England from Rome towards the end of 1681, and married Mary Tooke, a daughter of the Auditor of the Exchequer. She is described as a charming gentlewoman of real personal merit. Their marriage continued very happily for fifty-five years, until her death in 1736. Three of their children grew to maturity; a son, who became a naval surgeon and died one year before his father, and two daughters who survived him.

Halley set up house, and made a small observatory, at Islington. He started observations on the moon, with the idea that, as it repeats its position very exactly after a period of about 18 years, or 223 intervals of new-moon to new-moon, a careful table of positions throughout one

complete 18-year period would provide a simpler method of finding the position at any particular time in any such period.

In 1683 he published his theory of the variation of the magnetic compass. An explanation of the way in which the direction of the compass altered was of major importance to navigation. In attacking this problem, Halley gradually worked out a theory of the magnetism of the whole earth. He thereby founded the new science of geophysics. While this is of great practical importance to navigation, and nowadays to radio communication and aerial rocket flight, it can also be regarded as a branch of astronomy, for the study of the physics of the earth as a whole is the study of the physics of a planet, and a guide to the physics of other planets and heavenly bodies.

At this time, shortly after he was married and founding new sciences, he became acquainted with Isaac Newton, who was fourteen years older. Newton was then known as a mathematician and physicist of outstanding ability who was leading the life almost of a recluse in Cambridge, devoting most of his attention to religion and alchemy.

The young Halley, who had largely taught himself from the works of the ancient and modern mathematicians and astronomers, was attempting to find the explanation of the culmination of astronomy up to that date: Kepler's three laws of planetary motion. He succeeded in proving that Kepler's third law implied that a planet revolving round the sun in a circle was attracted to the sun by a force that varied inversely as the square of the distance. In spite of possessing excellent knowledge and skill in

geometry he was unable to prove that this was true if the planet moved in an ellipse with the sun in one focus. He consulted other members of the Royal Society who were known to have considered the problem, in particular Christopher Wren, who was twenty-four, and Robert Hooke, who was twenty-one years his senior. He discussed it with them in a London coffee-house early in 1684, where, according to his own account, 'I met with Sir Christopher Wren and Mr. Hooke, and falling in discourse about it, Mr. Hooke affirmed, that upon that principle all the laws of the celestial motions were to be demonstrated, and that he himself had done it. I declared the ill-success of my own attempt; and Sir Christopher, to encourage the enquiry, said, that he would give Mr. Hooke, or me, two months' time, to bring him a convincing demonstration thereof; and besides the honour, he of us, that did it, should have from him a present of a book of forty shillings. . . .'

Halley made further attempts to solve the problem, but failed. Then he thought of Newton, who had some years before discussed the subject with Wren and Hooke. He went up to Cambridge in August 1684, and asked for Newton's mathematical aid. To Halley's amazement, Newton told him he had solved the problem years ago.

Halley returned to London in the greatest excitement, perceiving the full significance of what Newton had done. Halley now embarked on the most important diplomatic operation in the internal history of science: the prompting and persuasion of Newton to complete and publish what was in him.

Halley recognized the magnitude of Newton's genius,

and was sufficiently younger to be able to defer to him gracefully. He was an accomplished astronomer and travelled man of the world, aged twenty-seven. He was a handsome man, rather tall and thin, with a fair complexion. He 'always spoke as well as acted with an uncommon degree of sprightliness and vivacity'. He had 'great extent of knowledge, and a constant presence of mind', so that he could answer questions readily, speaking to the point with good judgment, and yet with politeness and sincerity. He was warm and generous, and loved people. In their presence, he became lively and interested, and they felt that he took pleasure solely in their company and ideas. This inspired a widespread affection for him.

While Halley was struggling to find the explanation of Kepler's laws, and becoming involved in the historic task of nursing the *Principia*, the Mathematical Principles of Natural Philosophy, out of Newton, he was assailed by serious family troubles. Halley's mother had died, and his father had married again when Halley was sixteen. His stepmother seems to have been a difficult woman, and Halley senior became queer. He disappeared from his home in March 1684, and his wife offered £100 reward for information of his whereabouts. His dead body was found in a river near Rochester in Kent. The jury at the inquest brought in the verdict that he was murdered, though it seems not unlikely that he had become deranged and had committed suicide.

The body had been found by a poor boy who had told a man about it. This man reported the matter, and claimed the £100 reward. The case was taken to court, and was heard by the notorious Judge Jeffreys, who, however,

belied his reputation on this occasion. He ordered £80 to be given to the poor boy, and £20 to the man.

Halley found his income much reduced, and he had to take legal proceedings against his stepmother to avoid being deprived of his inheritance. Nevertheless, by the autumn of 1684 he had persuaded Newton to communicate eleven of the fundamental propositions of the theory of gravitation to the Royal Society. He, together with Newton's friend Paget, was commissioned by the Society 'to keep Mr. Newton in mind of his promise' to present an exposition of his new theory to the Society.

It involved the application of mathematics by new methods, not only in astronomy, but in the whole of physical science, and provided the mathematical theory of a vast range of phenomena in solids, liquids and gases, besides the movements of the heavenly bodies. Halley persuaded Newton to work this out in a systematic, logically connected book. Newton wrote the whole masterpiece in about fifteen months. A copy of the manuscript was presented to the Society, which ordered it to be printed. Halley undertook to see the work through the press, to protect Newton from all trouble and irritation. Then the Society found that it was short of money and had not the resources to print the work, so Halley also took over the financial responsibilities to the printers, in spite of his personal financial difficulties. In addition, he supplied Newton with a good deal of the material for the section on comets.

Newton's mental effort in composing his *Principia* was probably the most intense that has yet been made by man. He was so intent on the science that he became

detached from the book, and almost uninterested in it. He even came to regard it as Halley's property because he was paying for the publication. This had fortunate results, for Newton, in one of his fits of anger over Hooke's claims to have preceded him in the theory of gravitation, told Halley that he proposed to restrict the book to mechanics, or the motions of bodies, and leave out the part consisting of the application to astronomy and the gravitation of the celestial bodies, or system of the world. This was the part in which there was by far the greatest immediate interest. Halley tactfully demurred, and in deference to him Newton agreed to keep to the original agreement on the ground that ' 'twill help the sale of the book, which I ought not to diminish now it is yours'.

Thus the final contents of the world's greatest scientific book were determined, not by sublime considerations of natural philosophy, but by considerations of what was needed to secure the best possible sales.

Halley chose an excellent format, and engaged two printers to get the book through the press quickly. He composed elegant Latin verses to introduce it to the reader.

Newton approved the production. Though he was much senior to Halley, and in comfortable circumstances when the latter was in financial difficulties, he was quite content to leave production matters, including the paying of the bills, to the younger man. Halley's skill in handling this psychological situation, his practical ability and his immediate grasp of a mathematical work that few grasped during the next hundred years, constituted an extraordinary combination of qualities.

Halley's family difficulties and labour on the *Principia* did not prevent him from pouring out a stream of other work. In 1685 he accepted the position of Clerk, or assistant secretary, to the Royal Society, at a nominal salary of £50 a year. As a paid official, he resigned his fellowship. He was re-elected fourteen years later, on giving up the clerkship.

During these fourteen years he contributed a great deal towards running the Society, like Hooke in his younger days. He edited the *Philosophical Transactions*, and undertook to produce one-quarter of the copy, which he kept up for seven years. He frequently provided experiments and discourses on physical, practical and even chemical problems, in addition to astronomy. He made experiments on the strength of forces exerted by magnets, and on heat, especially in its effect on expanding and evaporating liquids, and on gases. In both of these subjects he had at the back of his mind their bearing on the physical processes of the earth, such as its magnetic field; and the circulation of the air in the global trade winds and monsoons, and of water in ocean currents.

He paid considerable attention to the problems of gunnery, joining with Papin (the inventor of the steam-digester, nowadays called the pressure-cooker) in experiments on the firing of projectiles by vacua (on the principle of the vacuum brake nowadays used on trains). He made extensive researches on diving bells, and on diving-suits which gave the wearer freedom of movement in investigating wrecks and the sea bottom. He reported curiosities, such as Indian seamless shirts, which, he said,

he would not have believed possible unless he had seen one.

While he was seeing the *Principia* through the press, which cost him 'a great deal of time and pains', he published his discovery of the bearing of barometric readings on astronomical observations. Change in density alters the refracting or bending power of the air, which must thus be allowed for, according to the height of the barometer. Besides these, he continued his astronomical observations of the planets, and published discoveries in pure mathematics, concerning the roots of equations.

This flood of activity was accompanied by a blossoming personal life. In 1688, the year after he had at last got Newton's masterpiece off the press, both of his daughters were born.

The spate of research went on. He discovered the slight increase in the speed of the moon in its orbit; he continued to work out in detail how observations of transits of Venus should be utilized to make a more exact measure of the distance of the sun; he showed how the new mathematical calculus invented by Newton could be used to simplify calculations in optics. It was from this paper that Lagrange, at the age of seventeen, first learned the possibilities of the new mathematics and turned from classical geometry to modern analysis, presenting and developing Newton's discoveries in the form in which they have been known and taught ever since, and incidentally becoming the greatest mathematician of the eighteenth century.

Halley was now about thirty-five, and still had no proper scientific post. In 1691 the chair of astronomy at

Oxford fell vacant, and Halley applied for it. The University authorities were more concerned about his religious views than his scientific qualifications. Bishop Stillingfleet doubted his orthodoxy, so Halley called on him to expostulate. When the Bishop began to question him in an impertinent manner, Halley said: 'My Lord, that is not the business I came about. I declare myself a Christian and hope to be treated as such'.

Halley had liberal religious opinions, which he openly expressed. His researches on the oceans and evaporation had drawn his attention to the saltiness of the sea, which, he saw, could be a measure of the age of the earth, which seemed to be very much older than was indicated by the Biblical account. He doubted the literal Adam-and-Eve story of the creation. His consideration of Hooke's theories of fossils, especially those found high up on mountains, reinforced his doubts, for these seemed to have been deposited a long time ago, and vast changes that had transported them to their present positions must have taken an immense length of time. Nevertheless, he asked a friend to intercede with Archbishop Tillotson, and inform him that he was 'not guilty of asserting he eternity of the world'. Flamsteed came to regard Halley as an infidel and a libertine, and exerted his influence as Astronomer Royal to prevent him from getting the chair of astronomy. Newton and Halley had not yet got the influence which they subsequently acquired. Halley was turned down, and the chair was given to David Gregory, a less important follower of Newton.

In 1704, thirteen years after Halley had been passed over for the chair of astronomy, the chair of geometry

at Oxford fell vacant, owing to the death of John Wallis. Oxford was then only too glad to get Halley, without any questions asked.

While Halley did not have conventional religious views, he was an outspoken Tory in politics, though he behaved like a Whig. This was due to his feeling of gratitude and loyalty to Charles II for early patronage and encouragement, and to Newton and his Whig friends for subsequent confidence and promotion.

Not the least remarkable of his researches in the busy years immediately after the *Principia* was his calculation of the size of atoms. He deduced from the thickness of gold leaf that they must be 'less than the 1/2433000000 part of the cube of the hundred part of an inch'.

He published his theory of the alteration in the variation of the magnetic compass from the exact north and south in 1692. He suggested that it was caused by a magnetized core in the earth, which revolves independently of the concentric upper layer, or layers. Halley's theory is of a kind which is now held to be most likely. It has been made more acceptable by the modern view that the core of the earth is liquid, so that rotary movements within it are easier to visualize.

One year later, in 1693, Halley published his analysis of the tables of births and funerals at the City of Breslau, which had been sent to the Royal Society. He calculated the odds that any person did not die before any proposed age, and carried out 'a most laborious calculation' of the price of annuities, or rates of insurance, for persons of various ages. He said that the tables showed 'how unjustly we repine at the shortness of our lives and think

EDMOND HALLEY

SIR WILLIAM HERSCHEL

at the age of 46

From a crayon copy of the oil painting by L. T. Abbott in the National Portrait Gallery

ourselves wronged if we attain not old age; whereas it appears hereby that the one-half of those that are born are dead in seventeen years' time'.

He concluded that population was kept down more by parents' fear of not being able to provide for their families, rather than anything in the nature of man himself. The 'inequal distribution of possessions' discouraged the size of the families among the poorer and larger section of the population. The figures for Breslau showed that there there 'might well be four times as many births' if the poorer section were better off. As the 'strength and glory of the king' is in the multitude of his subjects, celibacy should 'above all things' be discouraged. While bachelors should be taxed, parents with large families should be given aid, those belonging to the poorer classes being helped especially by seeing that they were provided with productive employment.

Halley's success in founding the theory of insurance depended on his mastery in computing, which he had developed for his astronomical investigations. He was not only a skilful user of logarithms, but improved the mathematical theory of logarithms itself.

He began his investigation of comets in 1695, and completed it in 1705. He worked out the orbits of no less than 24 different comets, the most spectacular being that of the comet of 1682. He showed it was probably the same as that observed by Kepler in 1607, and of earlier comets which had appeared at intervals of 75 or 76 years, in 1456 and 1531. He explained the variation in the period of return as due to the gravitational attraction on the comet as it passed near the planets Jupiter and Saturn.

He calculated that it would reappear in 1758, which would be after his own death. Halley said that if the comet did return according to his prediction, then 'impartial posterity will not refuse to acknowledge that this was first discovered by an Englishman'. The comet duly reappeared, sixteen years after Halley's death, first seen on Christmas Day 1758.

Halley incidentally proved that comets do not revolve round the sun in the same plane as the planets, but in orbits at random angles to this plane.

He accomplished many other things before he published this masterpiece.

When Newton became Warden of the Mint in 1696, he helped Halley by finding a post for him. He appointed him his deputy in the provincial mint set up at Chester, but after this was closed in 1698, he was again out of a job, and came back to London. Peter the Great visited England in this year, and Halley was recommended as an adviser to him on naval and scientific matters. Halley's strong intelligence and personality appealed to Peter. They became personally friendly, and Halley was very welcome at Peter's table. It is said that on one particularly convivial occasion, Halley wheeled the monarch on a barrow through a yew hedge in the garden.

Halley's investigations on the earth's magnetism prompted him to suggest that a map of the earth's magnetic field would provide a simple way of finding longitude. This led to his being appointed commander of the first English oceanic expedition for scientific research. He was appointed by William III in 1698 to undertake a survey of the direction of the magnetic compass over the Atlantic

Ocean, with the aim of benefiting navigation. He was to determine the longitudes and latitudes of British settlements in America, and 'attempt a discovery of what lands lay to the south of the Western Ocean'. He was given the command of H.M.S. *Paramour*, a small merchant-type vessel called a pink, designed to have extra space for stores. It displaced only 89 tons, and carried ten guns.

As Halley was not a professional seaman he asked that one of the warrant officers should be made his lieutenant. This man mutinied and persuaded the crew to disobey Halley because he had 'not the whole sea dictionary so perfect as he'. It appeared that the lieutenant four years before had written a book which had been referred by the Admiralty to Halley, who had reported on it adversely. The rejected author tried to take advantage of the unusual situation to get his own back on his adverse reader, and succeeded to a considerable extent in carrying the crew with him against a land-lubber captain. But he had to deal with no ordinary man. Halley confined the lieutenant to his cabin, and navigated the ship himself, in spite of his recalcitrant crew, back to England. The lieutenant was court-martialled and cashiered, and Halley set sail again, now as the commodore of two ships.

He sailed down the Atlantic until he 'fell in with great islands of ice, of so incredible a height and magnitude, that I scarce dare write my thoughts of it. . . .' He had come to the frontiers of Antarctica. He nearly lost his ship in fog and ice, but succeeded in returning without the loss of a man, though one cabin-boy was swept overboard.

Halley made a chart of the magnetic compass over the

Atlantic, joining the places with the same magnetic variation by a continuous line. The chart was of great practical value to navigation. His method of representing the distribution of physical quantities over the surface of the earth, or any other region, has been of great value in several branches of science. It enables large collections of data to be represented in an orderly way, so that their general features become evident. When these have been recognized, the scientist can investigate their causes. Halley subsequently extended his magnetic sea-charts to the whole world.

He was commissioned in 1701 to survey the coast, headlands and tides of the English Channel. He reported that he had discovered, with more success than he had expected, 'the general rule of the tides in the Channel'.

In the following year he worked on methods of surveying enemy coast, and suggested the use of sound in conjunction with charts for measuring the distances of targets.

Halley's skill as a military engineer caused Queen Anne to send him to advise the Emperor Leopold on the fortification of the Dalmatian coast. Leopold was exceedingly pleased with him, and took a fine diamond ring off his finger and presented it to him. Halley and the emperor's chief engineer fortified Trieste and other places. After these works were finished in the autumn of 1703, he returned to England.

Then John Wallis died, and Halley succeeded him as professor of geometry at Oxford. He immediately became active in a new field of work appropriate to his professorial chair. He published a series of fine editions of the great geometers of the ancient world. The Bodleian

Library had an Arabic manuscript of one of Apollonius's works, a portion of which had been translated by an Orientalist. From this Halley taught himself geometrical terms in Arabic, and then completed the translation. He even detected corruptions in the Arabic text, and suggested to Orientalists what had probably been written in the original; in several instances, his emendations were found to be very probably correct. He reconstructed one of the last books of Apollonius from the commentary on it by Pappus, and in 1710 he published a magnificent edition of Apollonius's masterpiece on the curves obtained by slicing a cone in various directions.

His stream of new results continued. He published his discovery of the star-cluster in the constellation Hercules, and gave a careful description of the sun at the total eclipse in 1715, which he observed from the roof of the Royal Society's rooms in Crane Court. Besides describing the corona he noted 'a very narrow streak of a dusky but strong red light', now known as the chromosphere. About this time he observed an aurora, and suggested that aurorae are produced by a luminous medium from the interior of the earth, whose shape was determined by the earth's magnetic field. Somewhat later, he calculated that a prominent meteor must have been at a height of 73 miles.

In 1716, at the age of sixty, he discussed the nature of nebulae, and suggested that these were 'nothing else but light coming from an extraordinary great space in the ether, through which a lucid medium is diffused, that shines with its own proper lustre'. He thought that they were larger than the whole solar system. This was a

brilliant recognition of the gaseous nebula, one of the two main types of nebula.

He published his great discovery of the movement of 'fixed' stars in 1718, when he was sixty-two. He compared the positions of the prominent stars Sirius, Arcturus and Procyon, given in the ancient tables of Hipparchus and Ptolemy, with those observed by contemporary astronomers, and showed that the differences were greater than the probable errors of observation. This led ultimately to the modern discovery that all stars are in motion, and to the foundation of modern cosmology. Two years later he followed this with an application of the theory of gravitation to the cosmological problem of the extent of the universe. He argued that it must be infinite, for if not, it would have a centre to which all the stars would gravitate.

He was appointed, in 1720, at the age of sixty-three, to succeed Flamsteed as Astronomer Royal. His official salary, like Flamsteed's, was £100 a year. His income was presently increased by granting him a naval captain's half-pay. The work of the Royal Observatory was not, however, of the kind most suited to him. Its purpose was to make accurate astronomical observations, especially for the improvement of navigation. He had not the patience to attend to all the details upon which the utmost exactitude in observation depends. He did not measure angles to the smallest possible fraction of a degree, nor did he use the most accurate clocks. After his death, it was noticed that the fixed mark on which the Observatory instruments were sighted, in order to align them correctly, had been obscured by a tree. It appeared that, for some

time at least, the alignment of the instruments had not been properly checked. His most considerable work at the Royal Observatory was on the moon. He pursued his old idea of observing it through 223 successive new-moon to new-moon periods, and carried it through with much determination in the years from 1722 to 1739. He derived from his researches on the moon the most accurate method of measuring longitude which had as yet been discovered.

His lunar researches led to some disagreement with Newton, who complained that he was backward in publishing his observations. Newton and Halley had formerly been engaged in a painful controversy with Halley's predecessor, Flamsteed. They had forced him, through government influence, to disclose observational data collected at Greenwich before he was ready to publish them. Newton wanted information in the first instance for his analysis of the moon's motions, but as he became old he demanded it more and more to show his authority and satisfy his sense of power.

Halley, who for much of his life had regarded himself as Newton's lieutenant, began to publish Flamsteed's observations, breaking an undertaking that this would not be done without Flamsteed's permission. Flamsteed became very embittered, and presently described Halley as a profligate scoundrel and atheist. To Flamsteed's malicious delight, Halley's edition of his observations was inaccurately edited and printed. Flamsteed succeeded in securing three-quarters of the edition, and publicly burnt them as 'a sacrifice to heavenly truth'. He arranged for the proper publication of his great catalogue of nearly

3,000 stars at his own expense. His masterpiece was duly published in correct and handsome style, but only several years after his death.

Now Halley found himself pressed by Newton through the very regulations that he had collaborated with Newton in organizing in order to exert pressure on Flamsteed. Newton considered that Halley's new observations of the moon should be published. Halley was not willing to publish them until he had completely worked out the theoretical implications, so that no one could forestall him in harvesting the theoretical fruits of his observational labours. Newton, now in his eighties, cited the orders that had been given by the Crown on the subject of the publication of data collected by the Royal Observatory. He was angered by Halley's delaying tactics, and Halley himself became nervous. He made an extraordinary mistake. He wrote to Newton in 1725 that he 'guessed by some symptoms' that he took it ill that he had not sent some calculations he had undertaken for him. He had made the elementary and 'intolerable blunder' of assuming the apparent motion of the sun to be in the opposite direction to what it is. 'I hope it will be easier for you to pardon me, than for me to pardon myself, who hereby run the risk of disobliging the person in the universe I most esteem'.

It has been said that Halley's delaying of the publication of his observations of the moon so upset Newton that it was the immediate cause of the onset of Newton's last illness. The truth seems to be rather that Newton, who had steadily grown more autocratic, had become inflexible, and could not bear to be crossed.

Apart from the question of character, the most remarkable feature of the incident is that Newton at eighty-two, and Halley at sixty-nine, were still concerned with fundamental researches in astronomy, and were taking them so seriously that they even disturbed their personal relations, after forty years of friendship and intimate collaboration.

Halley had a strong constitution, and suffered no serious illness in his long life, until he had a slight stroke in 1737, at the age of eighty. His wife had died in the previous year, and perhaps the end of their exceptionally happy life together was too severe a shock for even his constitution. He nevertheless continued his astronomical observations and social life until the age of eighty-three. His physique then disintegrated. He presently became tired of the doctor's medicines, called for a glass of wine, drank it, and expired. His characteristic cheerfulness and his strong memory and judgment continued to the end.

Halley died on 14 January 1742, and was buried, according to his wish, beside his wife, in the parish church of Lee, near Greenwich.

The question with Halley is not why he is famous but why he is not more famous. His discoveries were original, profound, varied and many. He wrote with splendid clarity, and he had a very modern outlook and insight. His personality was equal to his gifts. It is usually said that his star was outshone by Newton's, and that he was unfortunate in living in the same period. This does not seem to be an adequate explanation. It is true that in his own lines Newton was incomparable, but Halley's range of work was wider, and more concerned with ideas that

have become of major importance in our own day. Newton was the older man whose work was the culmination of a historical period and way of life. He created the mathematical astronomy which was the chief scientific need in a period when the navigational and astronomical problem of longitude was a fundamental concern of the national life. Newton attacked the problems of his period by individual effort, in the same spirit as the contemporary explorers and merchants. He had few pupils and created no school of research.

Halley, fourteen years his junior, succeeded with his superb abilities in constituting himself his lieutenant. Though his personality was very different, he adopted many of Newton's interests and attitudes. He was the first Newtonian scientist. He also resembled Newton in his method of work. He too did everything himself, and had few pupils and created no school.

Halley's modesty in so much subordinating himself to Newton caused him for long to be regarded as a lesser Newton. He was not, however, merely a Newtonian. As a younger man, he had his foot in the next generation. He was the bridge between the science of Newton and the new science which was coming into existence with the approaching industrial revolution.

His most original work and ideas belonged to the future. His fame is still increasing, and today he is saluted as one of the most richly talented and significant Englishmen of his time, besides being the eminent astronomer who forecast the return of the comet named after him.

REFERENCES

Correspondence and Papers of Edmond Halley, arranged and edited by Eugene Fairfield Mac Pike. Clarendon Press.

Edmond Halley. Papers by A. Armitage and Colin A. Ronan. Memoirs of the British Astronomical Association: Vol. 37, No.

Halley (by Augustus de Morgan) *Cabinet Portrait Gallery of British Worthies*: Vol. XII, 1846.

IV

WILLIAM HERSCHEL
1738–1822

THE theory of gravitation concentrated the attention of astronomers on the sun and planets. For a hundred years they were absorbed in working out its implications. This required the development of subtle mathematics to make the calculations, and very exact astronomical observations to provide data to check the theoretical predictions.

In spite of Halley's discovery that certain 'fixed' stars were moving, the study of the universe beyond the solar system was neglected. William Herschel recognized this, and decided to investigate the universe of the 'fixed' stars. He thought out the methods which would be appropriate to do this, and invented, and made with his own hands, the apparatus for applying them.

His outlook was profoundly original, and his technical skill and energy were almost superhuman. He grew up outside academic life and professional astronomy. He had a natural self-tutored genius. He made extraordinary discoveries appear so simple that it seemed as if anyone who took the pains could have achieved them.

When Herschel first became interested in astronomy, virtually nothing was known about the distances of objects outside the solar system. Light from the most distant planet takes only an hour or two to reach the earth, but

how long it took to come from the 'fixed' stars was a matter of speculation.

The poet Thomas Campbell reported a conversation with Herschel in 1813, when the astronomer was seventy-four. He described him as 'a great, simple, good old man'. Any questions put to him he laboured 'with a sort of boyish earnestness to explain'. Herschel told him that he had 'observed stars of which the light, it can be proved, must take two million years to reach the earth . . . nay more, if those distant bodies had ceased to exist millions of years ago, we should still see them, as the light did travel after the body was gone. . . .'

He had extended the scale of the measurement of astronomical distances, in terms of the speed of light, from hours to millions of years. The size of the stellar universe is still most graphically measured in millions of light-years. The giant 200-inch telescope at Palomar, a technical development of the big reflecting telescopes made by Herschel, detects nebulae at a distance of 4,700 million light-years, and the radio-astronomers are detecting radio stars at still greater distances.

Their mighty advances on Herschel are far less than his on his predecessors. The modern view of the universe, for all the discoveries of the last hundred years, is essentially Herschel's. If he were able to return to the world today he could assimilate the new facts and theories without disturbing his basic outlook.

Herschel was helped to his highly original view by entering astronomy from an entirely different profession. Until he was forty-three he made his living as a performer, teacher and composer of music. He never passed

through the school of mathematical astronomy in a university, nor was he trained in any of the official observatories with their emphasis on measurement and precision. This enabled him to avoid the preoccupations and conventions of the astronomy of the time, and to realize that the kind of telescope required for the exploration of the outer universe was quite different from that for the exact measurement of the solar system.

In order to investigate very distant objects it is first necessary to concentrate sufficient light from them to make them visible; they must be seen before any measurements can be made. In a word, a telescope for the exploration of the depths of space must be designed for penetration rather than precision. Telescopes of this type should have wide mirrors or lenses, and the eyepiece and subsidiary parts should be designed so that as little as possible of the collected light is wasted.

The instrument makers with their professional pride in fine workmanship made very precise instruments of moderate size, for which there was a demand. They were particularly interested in making refractory telescopes with lenses. One of them, Dollond, had discovered how to make such telescopes with images which were free from blurring coloured fringes, a feat which Isaac Newton himself had believed was theoretically impossible. They were very proud of having corrected Newton.

It is, however, extremely difficult to make such lenses very wide, because of the difficulty of getting big uniform pieces of glass. Herschel therefore attempted and succeeded in making bigger and better telescope mirrors than had ever been made before.

It was typical of his approach that when he wanted the very maximum penetrating power he slanted the mirror in its tube, so that while it produced a slightly distorted image it delivered twice as much light to the observer's eye, thus rendering visible things which otherwise could not be seen. He subordinated precision to discovery.

Herschel was born at Hanover in Germany on 15 November 1738. He came of a family that was probably of Jewish descent, but had long been Christian, and in the service of the local princes. His grandfather was one of the Elector's palace gardeners. His father, Isaac Herschel, was apprenticed to gardening, but being passionately fond of music, he secured some instruction and became the oboist in the band of the Hanoverian Guards. He and his wife, Anna Ilse Moritzen, had numerous children, six of whom survived. The third of these was Friedrich Wilhelm, who was to become the great astronomer, under the anglicized name of William.

All of Herschel's children had musical ability. He had a tiny violin made for the infant William, who could remember being made to stand on a table when he was four, and give a performance. Besides his musical brothers, his elder sister Sophia became the mother of five sons, all of whom found places in George III's court orchestra. His sister Caroline was particularly remarkable. She was eleven years younger, and after being taught by him to become a first soprano in Handel's *Messiah*, gave him fifty years of astronomical collaboration, and lived until she was ninety-eight.

William did not marry until he was fifty. His bride,

Mrs. Mary Pitt, was a widow of thirty-eight, with a grown-up son. They had only one child, John Frederick William Herschel, born four years later. He became one of the most influential scientists of the early nineteenth century. At the age of twenty-one, he joined Peacock and Babbage, the inventor of the computer, the forerunner of the 'electronic brain', in modernizing English mathematics after the century of relative stagnation following Newton. He was put up for election to the Royal Society while he was still a minor, and was elected shortly after his twenty-first birthday. Among many other achievements, he extended his father's review of the northern to the southern stars, so that father and son gave a complete picture of the structure of the stellar universe.

William Herschel secured for his brilliant son the best possible education. The Herschels did not owe their achievements to genius alone. Though William Herschel's mother was illiterate, he himself had received a good education when he was a boy. His father sent him to the Garrison School in Hanover, where he was competently taught Latin, mathematics and French. William was engaged at the age of fourteen to play the hautboy, an old-fashioned form of oboe, and the violin, for the Guards. His earnings were spent on securing extra tuition in mathematics and philosophy.

Isaac Herschel was interested in science and had some knowledge of astronomy, which he imparted to William. Caroline Herschel said that she could remember that her father and brothers used to refer to Leibnitz, Euler and Newton in their talks about science. One of William's

teachers was interested in metaphysics, and stimulated his interest in this subject.

When he visited England with the regiment as a boy of eighteen he spent the whole of his savings on buying a copy of Locke's *Essay concerning Human Understanding*. One of his earlier acquaintances in Britain was David Hume, who entertained him after he had given musical performances in Edinburgh. Herschel said that an insatiable desire for knowledge had been awakened in him in his youth, and henceforth he looked for his future happiness and contentment solely in the pursuit of it. It seems that the tastes of band-boys in the Hanoverian Guards were more cultivated than military.

The musical and scientific studies of the Herschel family were suddenly upset by Frederick the Great, who in 1756 precipitated the Seven Years' War. The French violently counter-attacked in the following year, and routed the Hanoverian Guards at Hastenbeck. When the battle began to go badly, Isaac advised his son, as a non-combatant band-boy, to flee. William ultimately made his way to Hamburg, where he was joined by his elder brother Jacob, who had also informally departed from the Guards. As William had been enrolled as a non-combatant, he was not strictly a deserter; his father later secured an official discharge for him in 1762.

The two brothers sailed for England and went straight to London, where William, almost penniless, at once obtained employment as an expert copier of music. William had to work very hard, not only to support himself, but his elder brother, who would not accept any appointment lower than first violin. After peace had

returned, Jacob went back to Hanover, to a place in the Court Orchestra, and left William to pay his debts. William remained in England, for if he had gone back he would have had to rejoin the Guards.

He found the competition among musicians in London very severe, so in 1759 he accepted an engagement at Richmond in Yorkshire by the Earl of Darlington, to lead the band of the Durham militia. When William arrived in Yorkshire he found that there were only three other musicians besides himself in the militia band, but two of the others were very good performers on the French horn, so he composed military music which showed their accomplishment to the best advantage.

He secured engagements as accompanist and teacher of music in many country houses in the North. He bought a horse to take him from house to house, sometimes riding fifty miles in a day, over moors and through rough weather. He devoted his leisure to composing symphonies, hoping to establish himself in the front rank. Though he did not succeed in this, some of his music is remembered. It has a cheerful vitality, like himself, and was warmly welcomed, particularly when it was new.

He worked hard at languages and the theory of music. This led him to study the mathematics of harmony, and thence to related branches of mathematics. At the age of twenty-two he pored over these topics in his lonely lodgings in the North. From Sunderland, where he lived for some time, he wrote long letters to his elder brother in Hanover, containing reflections on his latest philosophical reading.

He sometimes thought of giving up the hard touring

life, performing in one country house or town after another, but he decided to stay in England, as he could earn three times as much as in Hanover. Sometimes he met influential persons in the country houses. On one occasion, at Halnaby, he was accompanied by the Duke of York, the king's brother, who was an accomplished violoncello player; but this did not lead to more settled work.

After four years as a travelling musician, from York to Edinburgh and Sunderland to Pontefract, he felt it essential to settle down. In 1762 he secured a post at Leeds. He wrote to his brother that some of the 'richest people' in this city, which he found a 'delightful place', had offered him the directorship of the public concerts, at a good salary. He remained in Leeds for four years.

During this period he found the musical life less and less intellectually satisfying. He moved on to Halifax in 1766, where his life reached one of its turning points. Mr. Bates, clerk to the Halifax Parish Church, and father of the noted musician Mr. Joe Bates of King's College, Cambridge, organized performances of Handel's *Messiah*. His son Joe returned from Cambridge to conduct and Herschel was engaged as leader of the orchestra. The Bateses supported Herschel's application for the post of organist to the Parish Church, in which a new organ was being built.

The bright prospect filled Herschel with enthusiasm. He passionately admired Handel, and started composing an oratorio of his own, to be called 'The Success of Satan against Man', taking the words from Milton's *Paradise Lost*. In the moments of leisure that he snatched from the

exaltation of Halifax life, he read Smith's mathematical treatise on *Harmonics*, and the works of Maclaurin. One of the Bateses noticed it and announced that 'Mr. Herschel read Fluxions!'

When the Halifax organ was finished, candidates for the position of organist had to play it to the local musical notabilities assembled in the pews. Herschel won the competition with the aid of the artifice of placing lead weights on two of the bass keys, which produced an impressive background of deep low sound to his own playing. He began his duties with enthusiasm.

He had scarcely started on these before he received the offer of an even more attractive position of organist to the new Octagon Chapel, which was being built at Bath. This was the first of the chapels built by private proprietors in that city, which catered for rich personages and invalids. Unlike Bath Abbey, in this chapel favourite preachers could be heard from seats near six large open fires, free from the cold, and the uncomfortable proximity of the lower classes.

Herschel went to Bath at the end of 1766. The nine years that he spent in the North were of great importance in forming his outlook. It was perhaps during this period that he began to acquire the spirit of the craftsmen of the impending industrial revolution. This helped him to make with his own hands the superb telescopes which, beside James Watt's steam engines, were among the great symbols of the new age.

It seems not without significance that the two great Hanoverians, Handel and Herschel, should have found a sympathetic understanding in the West Riding. Handel

has continued ever since to be in a sense the musician of the Yorkshire industrial workers.

As the Octagonal Chapel was private property and seats in it were charged for, the managers could pay good fees. Herschel found profitable employment not only in the chapel, but in the orchestra which gave subscription concerts and played in the Pump Room. The distinguished musician Linley, the father of the beautiful singer Elizabeth Linley with whom the dramatist and statesman Richard Brinsley Sheridan eloped, was also a member. Linley arranged for Herschel to give his son lessons on the violin and in mathematics. After the young man went to Oxford he used to write to Herschel for help with his mathematical problems.

With his Bath engagements and others in various parts of the south of England, Herschel was earning by 1771 the handsome income of £400 a year. He was absorbed in his work and intellectual interests, and in helping the large Herschel family in Hanover. Three of his brothers came to Bath at various times, and were given support.

His sister Caroline was almost a dwarf, only about five feet high. Her father had told her she could have no hopes of marriage, as she was neither handsome nor rich. Her illiterate mother had brought her up to wait on her eldest brother. When one of the younger brothers came to Bath he told William that Caroline had a good voice which could be trained, so Herschel in 1772 went to Hanover to bring her to Bath. He could persuade their mother to part with her only by undertaking to pay for a servant in her place.

Herschel had secured the place of clerk to the Octagon

Chapel for an old Leeds friend, Mr. Bulman, who had been kind to him in Yorkshire, and had since fallen on hard times. He took a comfortable house, part of which he let to Bulman, whose wife acted as housekeeper. Mrs. Bulman looked after him very comfortably, but tension soon arose after the arrival of Caroline, who gradually took over the management of the household, and whose ways of doing things were different. She was a most determined person, subsequently described by Herschel's daughter-in-law as 'the tough little German sister'. The Bulmans presently returned to Leeds.

In 1773, the year after Caroline came to Bath, Herschel began his first serious studies in astronomy. Though he worked 14 to 16 hours a day on his highly successful musical activities, he started to write a book on harmony, and used to attack problems on the calculus as a recreation after he went to bed at night.

He read some fascinating accounts of what had been revealed by astronomical telescopes, and this fired his desire to possess one of his own, so that he could see these things with his own eyes. He bought a quadrant and various books bearing on astronomy, in particular the book by Ferguson, the shepherd-boy who became an astronomer and received a pension of £50 a year from George III.

Herschel hired small telescopes, and immediately desired to possess bigger ones. As these were expensive, he started making them himself. He bought lenses from London and fitted them into tubes made at home. His first telescope, of the refracting type, magnified forty times, and he peered with intense enthusiasm at Jupiter and its

satellites. He quickly made still bigger refracting telescopes, but ran into difficulties with the sagging and manipulation of the long tube.

Up to his time, the 'fixed' stars had been regarded as mere specks of light on the inside surface of 'that inverted bowl which is the sky'. They were thought of as points on a surface, not as objects distributed through space. Herschel got rid of this two-dimensional view of the stars, and saw them in three dimensions.

In 1784 he defined his aim as the obtaining of 'some faint knowledge of, and perhaps . . . partly to delineate the *Interior Construction of the Universe*'. This was to be done 'By applying ourselves with all our powers to the improvement of telescopes . . . and the turning them with assiduity to the study of the heavens'. He saw that for the utmost penetration, wide aperture, or lenses or mirrors of large diameter were needed. In fact, doubling the aperture doubled the distance at which very faint objects became visible. He went over after a few months from lenses to mirrors, because these could be made in large sizes much more easily and cheaply.

Herschel set about making a reflecting telescope in the autumn of 1773, on the basis of information he found in a popular treatise on optics. He learned that there was a man in Bath who polished reflectors as a hobby. He sought him out, bought all his tools and half-finished mirrors, and arranged that he should show him how he carried out the polishing. Within a few weeks he had more than mastered his mentor's technique. He had a number of metal discs for mirrors cast, according to a recipe he had acquired with the tools. The metal was an

alloy of about three parts copper, one of tin and a small amount of antimony.

He ground and shaped the discs as well as he could, and before the end of the year he had given them sufficient polish to make them ready for mounting in tubes. He made no less than two hundred mirrors before he got one that was satisfactory. He did this while carrying out all his musical duties, and teaching half a dozen students a day. He filled his house with tools. One of his brothers had a large lathe in a bedroom, and a cabinet-maker was set to work in the drawing-room, making telescope tubes and stands. For these purposes, Herschel utilized cocus wood, the kind out of which his oboes were made.

One aspect of Herschel's telescope-making was particularly striking; he gradually developed it on industrial lines. He kept the refinements of his processes secret, and made telescopes for profit. This ultimately provided an important part of his income. He kept a list of 76 telescopes which he had sold for £15,000. His methods of manufacture were not published until they were rediscovered at great expense and labour by the Earl of Rosse in the middle of the nineteenth century.

Herschel organized teams of workmen for polishing the mirrors for his biggest telescopes. He had twenty-four men working continuously in two twelve-hour shifts polishing his biggest mirror. Each team of twelve wore dungarees with numbers on their backs, so that he could give individual orders as they worked in combination. He no doubt transferred his experience as an orchestral conductor to this industrial process, but he also had as good an understanding of workmen as he had of musicians.

He made numerous metallurgical experiments on casting discs from alloys of various composition, and he investigated the reflecting powers of different metals.

He made at least 430 telescope mirrors by hand. The most spectacular part of the process was the final hand-polishing, which he practised for fifteen years before he got a machine. In order to obtain the finest finish it was necessary to complete the final polishing without interruption. On one occasion this took sixteen hours. Caroline fed him as he laboured, putting morsels of food in his mouth as if he were a Channel swimmer. She read stories and novels to him, such as *Don Quixote* and the *Arabian Nights*, and the novels of Fielding and Sterne, to relieve his boredom.

In addition to his other qualities, his physical strength was remarkable. He made several mirrors at a time, and then picked out the one which was found to work best, proceeding on the principle of what is nowadays called the statistical control of production.

While these mechanical abilities were very impressive, especially to those who saw him at work, the superiority of his mind and ideas was still more striking. Though he supplied magnificent telescopes to many of the best astronomers in the world, no one succeeded in making discoveries with them in the least comparable to his own.

He completed his first successful reflector in 1774. His first recorded astronomical observation was of the Orion nebula. This marked the beginning of his career as an astronomer. He was then thirty-five years old.

He started his systematic study of the heavens in the following year. He said that he was guided by the

determination to accept nothing on faith, but to see with his own eyes what others had seen before him. He reviewed the heavens systematically, being careful never to pass by the smallest portion without due investigation. He repeated the complete review four times within nineteen years, each time with more perfect instruments.

While making the second of his reviews, he noticed on 13 March 1781 a small star of uncommon appearance, which he at first suspected to be a comet. As it was kept under observation it soon became evident that it was a planet. Calculations showed that it must be revolving round the sun at a distance about twice that of Saturn, then the most distant of the known planets.

No planet had been discovered since the dawn of history, and Herschel at once became famous. He wanted to call his planet Georgium Sidus in honour of George III, but the name Uranus, suggested by Bode, was generally adopted.

Herschel's friends solicited royal patronage for him. He was ordered to demonstrate his telescopes and discoveries at Court, and in 1782 George awarded him a pension of £200 a year. He was expected to set up his telescope near Windsor, so he moved from Bath to Datchet.

Herschel did not become a professional astronomer until he was forty-three. Many people thought that the discovery had been a happy accident. Herschel said that this was a mistake. 'In a regular manner I examined every star of the heavens, and it was that night *its turn* to be discovered. . . .'

When the astronomical records were searched, it was found that Uranus had been seen at least twenty times

before. Flamsteed saw it in 1690, and four other times; Lemonnier saw it eight times in one month, and Bradley had also seen it. These great astronomers had all taken it for an ordinary star. Herschel's success was a brilliant demonstration of Pasteur's saying that discoveries come only to the mind that is prepared to recognize them.

As part of his plan for investigating the structure of the universe, Herschel required to know two things: the way in which its contents are arranged, and its size. The first was to be elucidated by his reviews of the whole heavens; the second was to be determined by measuring the distance of the stars. This would give the scale on which the universe was constructed.

All attempts to measure the distance of stars by direct surveying methods had failed. Stars had been observed from opposite ends of the earth's orbit, which gave the widest available base-line. If the observation had been sufficiently exact, then a slight difference in direction of the light arriving at the two respective bases would have been detected. The instruments were not, however, sufficiently sensitive to reveal this slight difference.

Herschel tried another method, which had been suggested by Galileo. There are various examples of very close pairs of stars in the heavens. In some cases one of them is bright and the other is faint. If the faint star is very distant from the earth, while the bright star is much nearer, the change in perspective when the pair is observed from different places in the earth's orbit will make the apparent distance between the two close stars vary. Herschel collected examples of pairs of stars which he thought would be suitable for the purpose. He chose

pairs which were all close enough to appear to the naked eye as one. In 1781, on the occasion of his election to the Royal Society after he had discovered Uranus and while he was still living at Bath, he submitted a catalogue of 269 such pairs, 227 of which were new discoveries. Three years later he sent a catalogue of 434 more, and in his last paper, published when he was eighty-two, he sent 145 more.

Herschel recorded the direction of the line joining each pair. In his first paper he wrote that it was too early to say whether one star might be revolving round another. Twenty years later he succeeded in showing that the line joining the two components of the well-known double-star Castor was changing its direction. Bradley had made a note of this direction 44 years before, and comparison with this observation left no doubt that the two stars were revolving round a common centre. Herschel estimated that the revolution of the two members of Castor took about 342 years, a result which is of the right order.

He reasonably concluded that the two stars were revolving under mutual gravitational attraction. He provided the first direct evidence that gravitation operates beyond the solar system, in the depths of space.

Thus Herschel, whose supreme achievement was to advance beyond the conventional Newtonian astronomy of the solar system, failed to make a direct measurement of the distance of the stars, but became the first to extend the Newtonian principle of gravitation to the explanation of the movements of bodies in outer space. As Herschel himself put it, he had, like Saul, gone out to seek his father's asses and had found a kingdom.

Herschel's last years at Bath were musically as busy as ever, but his music became inextricably mixed up with astronomy. He moved to a house outside the city in order to get a better garden for erecting his telescopes, and found that while it was convenient for astronomy, it was inconvenient for his pupils, and for himself to go into town to perform his musical duties. He moved back, to a house without a garden, and then fixed his telescopes up in the public street in front of his house. All kinds of people stopped to have a look at the stars, which Herschel with his irrepressible enthusiasm was only too glad to provide. He made some helpful friends in this way. One of these, Sir William Watson, introduced him both to scientists in Bath and to the Royal Society in London.

His pupils found that during lessons he often kept an eye on the sky. One of them described how, on noting a gap in the clouds, Herschel dropped the violin with which he was giving instruction, and rushed off to look at a star which had just appeared, and in which he was particularly interested.

He was overjoyed at the escape from his musical labours provided by the king's pension, even though at the sacrifice of more than half his income. When he mentioned that his salary was to be £200 a year, Watson exclaimed: 'Never bought Monarch honour so cheap'. This was not Herschel's view. He said he would live cheaply in the country, on bacon and eggs, if necessary. His sister Caroline, who continued to act as his housekeeper and astronomical assistant, found the cost of living at Datchet higher than it had been at Bath. Servants were more difficult to get, eggs were three times as expensive, meat was three

pence a pound dearer, and coal more than double the price. George did not give Herschel much money, but he gave him status, which greatly increased Herschel's opportunity for earning money.

The old house near the river was subject to fogs and floods, but Herschel was not put off. While he was compiling his second collection of observations of double stars, he found that his seeing was not spoilt even in fog, and when condensed moisture was streaming from the mirror of his telescope. He sat on a scaffolding sixteen feet high, without any protection from the weather; as it got colder and colder, he piled on more and more clothes. Visitors found him observing in twenty degrees of frost. He worked in the open because he found that the telescope was not at its best unless it was at the same temperature as the air. On clear winter nights he would observe for twelve hours, with breaks every four hours or so for coffee.

As he took the readings on his telescope he called them out to Caroline, who was sitting in a room in the house nearby. She was an intelligent, tireless and exact assistant. Her collaboration was of immense help, as it relieved Herschel of the necessity of recording his own observations, and thus of continually having to use a light, and losing the adaptation of his eyes to the dark. Herschel systematically exercised his eyes, and practised seeing for whole nights. He said it was an art which must be learned, and it would be as unreasonable to expect an untrained person to observe skilfully with an astronomical telescope as it would be to ask him to play one of Handel's fugues.

When it became fashionable to possess a Herschel telescope, the statesman William Pitt bought one for 100 guineas, but could make nothing of it, in spite of a 14-page brochure of instructions neatly written by Caroline. Pitt asked Canning how to use it, and Canning asked Dr. Burney, the musician-friend of Herschel, who was also interested in astronomy, handing him the brochure. Burney was careful to put it in a place where everyone would forget about it, for he also did not feel equal to demonstrating Herschel's telescope.

As Herschel and his assistants worked in the dark, they occasionally had accidents, mishandling the telescope and barking their shins on beams and poles. On one occasion Caroline slipped in the snow and fell on a sharp hook in the machinery of the telescope, like the meat hooks used for holding up sides of beef. It sank into her thigh, and her brother and his colleagues rushed to her aid. They were unable to release her without leaving about two ounces of her flesh behind. She tied her wound up with a handkerchief, and after a few days was provided with ointment and lint by a doctor. Six weeks later she feared she might lose her limb, but her doctor told her it was mending well, remarking that if a soldier had received such a wound, e would have been ordered to hospital for six weeks.

After the strenuous nights, Herschel spent the days making new telescopes, and his sister in writing-up the previous night's observations. From time to time Herschel had to take a telescope to the Queen's Lodge at Windsor, to demonstrate the latest wonders of the heavens to the king and his family.

During his first years as royal pensioner Herschel

became hard up, and had to spend his savings. His friends made various efforts to get his situation improved. He moved into a house at Slough, where he lived for the rest of his life; it had been occupied by one of the king's pages. He cut down all the trees in the garden and set up his 20-foot telescope. The stables were converted into an apartment for his sister, and the outhouses into laboratories and workshops for telescope-making.

The king granted him £2,000 for making a giant 40-foot telescope with a mirror 48 inches in diameter. This was supplemented by a further £2,000, and a grant of £200 a year for upkeep. Catherine the Great ordered several telescopes from him, and the King of Spain a 25-foot instrument for which he paid £3,150. It was completed in 1805, and Herschel was packing it at the very moment that the Battle of Trafalgar was being fought off the Spanish coast. During the long contest with Napoleon, the relations between scientists in the opposing countries were not as entirely broken as in modern wars. Herschel himself visited Paris during the uneasy peace of Amiens, in 1802. In the previous year he had been elected a member of the French Institute, and Napoleon had granted the equivalent of £1,200 in platinum for the construction of a copy of one of his telescopes.

Herschel was splendidly entertained by Laplace and others, and was surprised by Mme Laplace, who 'received company abed; which to those who are not used to it appears very remarkable'. His reception by Napoleon is celebrated. Herschel said that Napoleon was very quick in seeing the point of any subject, but pretended to know more than he did. Napoleon asked him various questions

on astronomy and the construction of the heavens, and Herschel's answers seemed to give him great satisfaction. Herschel said that Napoleon 'also addressed himself to Mr. Laplace on the same subject, and held a considerable argument with him in which he differed from that eminent mathematician. The difference was occasioned by an exclamation of the first Consul, who asked in a tone of exclamation or admiration (when we were speaking of the extent of the sidereal heavens): "and who is the author of all this!" Mons. De La Place wished to show that a chain of natural causes would account for the construction and preservation of the wonderful system. This the first Consul rather opposed. Much may be said on the subject; by joining the arguments of both we shall be led to "Nature and nature's God" . . .'

After this, they discussed horse-breeding.

Herschel started his greatest work in 1784, after his attempt to measure the distance of the stars directly had failed. He devised his method of star-gauging, for investigating the arrangement of the stars in the universe. He assumed that the stars are more or less evenly distributed. Hence, if more stars are seen in one direction than another, he concluded that the stellar universe extended further in the first direction than in the second, the extent being proportional to the density of the star-population in the respective directions.

He made what he called 'sweeps' of the heavens with his 20-foot telescope. These consisted of looking at successive circular portions of the heavens, each about one-quarter the area of the sun or full moon, and counting the number of stars that were visible. In 1785 he published

the result of such 'sweeps' in 683 regions of the heavens. He found that in some directions he could see only one star at a time, while there were others in which he could see six hundred. He estimated that on one occasion 116,000 stars had passed before his eye in a quarter of an hour. The distribution of the stars was roughly the same as that which appears to the naked eye in the Milky Way. Herschel's counts of stars showed that the galaxy was about five times as broad as thick. Its shape was rather like that of a grindstone, which had been suggested by Thomas Wright in 1750 and adopted by Kant. Thus Herschel converted their speculations into a scientific theory on a basis of numerical counting or measurement.

The assumption that the stars are more or less evenly distributed was obviously only very approximately true; Herschel therefore paid special attention to all the conspicuous departures from evenness, especially the star-clusters and nebulae. About 150 of these had already been discovered, but he increased the number to 2,908. He concluded that in close clusters, and in various parts of the Milky Way, the stars are packed together more tightly than ordinarily, and in one of his many Sibylline thoughts, when he foresaw the scientific ideas of the future, he remarked: 'these clusters may be the laboratories of the universe, if I may so express myself, wherein the most salutary remedies for the decay of the whole are prepared'.

His huge advance in knowledge of the nebulae enabled him to classify them into at least eight different types. As early as 1786 he reported: 'I have seen double and treble nebulae, variously arranged; large ones with small, seeming attendants; narrow but much extended, lucid

nebulae or bright dashes; some of the shape of a fan, resembling an electric brush, issuing from a lucid point; others of the cometic shape, with a seeming nucleus in the centre; or like cloudy stars, surrounded with a nebulous atmosphere; a different sort again contain a nebulosity of the milky kind, like that wonderful inexplicable phenomenon about θ Orionis; while others shine with a fainter mottled kind of light, which denotes their being resolvable into stars'.

He realized that the Milky Way might appear as a nebula or 'island universe' when seen from another nebula or 'island universe'. With his powerful telescope he was able to resolve many nebulae which appeared to be continuous into clusters. He arranged them in a series insensibly changing from coarse clusters down to a fine milky nebulosity, and concluded that the speculations of Wright and Kant, that nebulae are assemblages of stars, or separate 'Milky Ways' forming 'island universes' far out in space, were basically correct. Herschel told Fanny Burney, the novelist and daughter of Dr. Burney, that he had discovered '1,500 universes'.

Herschel gradually recognized that many of the nebulae were not in fact of the 'island universe' type. His observations of the planetary nebulae, in which a bright star is surrounded by a disc of shining nebulosity, convinced him that some nebulae did not consist of stars, but of 'a shining fluid, of a nature totally unknown to us', as Halley had previously suggested.

Herschel's later studies of the distribution of those nebulae and clusters led him to conclude that most of them belonged to our own galaxy. He devoted more attention

to the working-out of the idea that the galaxy is a system of stars which had condensed out of a vast primeval nebula of gas, by gravitational attraction.

The notion that many of the nebulae were 'island universes' like the galaxy itself, but isolated far out in space, fell into the background, and most of his immediate successors thought it was mistaken. They assumed that the stellar universe ended at the frontiers of the galaxy. Herschel never gave up his notion of 'island universes' altogether, and in 1924 conclusive proof was at last obtained that they did indeed exist; once more his profound insight was confirmed.

The continuous gradation in the types of nebulae led Herschel as early as 1789 to propound an evolutionary theory of the universe. He said that the degree of closeness of the packing of the stars in the clusters and nebulae was a measure of their age. There was a 'clustering power' that was concentrating the more dispersed shadowy nebulae into brighter more condensed clusters. He said that 'this method of viewing the heavens seems to throw them into a new kind of light. They are now seen to resemble a luxuriant garden, which contains the greatest variety of productions, in different flourishing beds; and one advantage we may at least reap from it is, that we can, as it were, extend the range of our experience to an immense duration. For to continue the simile I have borrowed from the vegetable kingdom, is it not almost the same thing, whether we live successively to witness the germination, blooming, foliage, fecundity, fading, withering and corruption of a plant, or whether a vast number of specimens, selected from every stage through

which the plant passes in the course of its existence, be brought at once to our view?'

Herschel's profound views on the evolution of nebulae and the cosmos excited less attention than we today would have expected. They were conceived before Charles Darwin was born, and they were in startling contrast with the almost universally accepted official view of the Established Church that the world was created in 4004 B.C. Herschel's insight was so great that even his own son was sometimes frightened by its boldness. John Herschel felt unable to include one of his most brilliant discoveries in his list of his father's achievements.

This was Herschel's demonstration that the sun, and the whole solar system with it, was moving towards the stars in the constellation Hercules. He proved that certain stars showed the same kind of change in perspective with time, as a pair of street-lamps, which appear to the driver of a vehicle to diverge, as he approaches them in the street.

Herschel suggested as early as 1783 that the sun was probably moving faster than the earth in its orbit.

He measured the relative distances of the stars by comparing their sizes as they appeared in different telescopes. If a star in a 48-inch telescope appeared the same size as a star in a 24-inch telescope, then it was twice as far away. He estimated in this manner that stars just visible to the naked eye would be about twelve times as distant as a bright star such as Arcturus. If Arcturus were removed to about nine hundred times its present distance, it would be just visible in his 20-foot telescope with an 18·8-inch mirror. His giant telescope with a 48-inch mirror should therefore reveal it at more than twice that distance.

Besides this unique work on the stellar universe, Herschel contributed much to other branches of astronomy. He discovered two satellites of Uranus, which proved to be revolving not in the same plane as the planet's orbit, but almost at right angles to it. He discovered two more satellites of Saturn, and measured the period of rotation of its famous ring. He showed that the moons of Jupiter always showed the same face to the planet, as the moon does to the earth.

He thoroughly studied the sun. His conception of it was a mixture of error and genius. He believed it was cold in the interior, and that it was inhabited. But his telescopic studies led him to the discovery of the infra-red rays. This arose out of the need for protecting the eyes against the sun's rays. In his earlier observations of the sun he seriously hurt his eyes, so he made a systematic investigation of the physical properties of the sun's rays, to devise a suitable protection. He found that this could be provided by placing a glass vessel containing water between the eyes and the eyepiece of the telescope, and tincturing the water with black ink.

Herschel proved that the infra-red rays beyond the red end of the visible spectrum could be reflected and refracted like 'invisible light'. He demonstrated that the amount of heat conveyed by the different coloured rays in the spectrum varied, and he characteristically pointed out that the chemical effects of rays of the different colours would probably be different. His discovery contributed both to the invention of photography, in which his son John had an important part, as the discoverer of the effects of 'hypo' on silver salts, subsequently used in 'fixing'

photographs; and to the foundation of the new science of photochemistry.

Herschel's studies of sunspots led him to suggest that the radiation from the sun varied. He suggested that such a variation might produce a corresponding variation in the plant-growth on the earth. It might be revealed by the examination of annual harvests of plants such as wheat, and to this end he examined the annual records of the price of corn at Windsor. This famous suggestion has inspired a great deal of research.

Herschel followed where his genius led him. His imagination flowered, like Shakespeare's, in a profusion which sometimes seemed undisciplined to those who had had a formal academic training. The learned Brougham lost patience with him. He complained in the *Edinburgh Review* that his 'space-penetrating power' was a regrettable compound of epithet and metaphor. He should have left the coining of words and phrases to the poets. His writings suffered from 'a great prolixity and tediousness of narration'. They were full of 'loose and often unphilosophical reflections, which gave no very favourable idea of his scientific powers, however great his merit may be as an observer. . . .'

As for his speculations on the influence of sunspots on the price of grain, 'since the publication of Gulliver's voyage to Laputa, nothing so ridiculous has ever been offered to the world. . . .'

Herschel's giant 40-foot telescope with its 48-inch mirror became one of the wonders of the world, and innumerable visitors went to Slough to see it. The huge instrument was, however, more of a success as a wonder

than as an astronomical telescope. The big mirror contained about a ton of metal. When attempts were made to cast it in the best optical quality of alloy, which was very brittle, the castings cracked. A less brittle but optically inferior alloy was therefore used. The mirror made from it tarnished easily, and was liable to be out of condition. The power of the telescope was so great that it could only be used on the rare occasions at Slough when the atmosphere was very clear and steady. The weight of the mirror and the size of the tube made manipulation difficult. The fact was that metallurgy and engineering had not progressed sufficiently far to solve the problems of making such a large mirror, and the convenient operation of such a big machine.

Herschel continued to do by far the greater part of his best work with his 20-foot telescope with the 18·8-inch mirror. This mirror weighed only 128 lb. The whole instrument was easily and rapidly manoeuvrable, and was far less dependent on exceptional weather conditions for good seeing.

The big telescope had other uses, besides occasional observing where very high power was essential. When George III was first brought to see it, during the process of construction, the 40-foot tube was laid horizontally on the ground. He was asked to walk through. It is said that when he was inside he turned to the Archbishop of Canterbury, who was following him with difficulty, and gave him his hand, saying, 'Come, my Lord Bishop, take my hand, I will show you the way to heaven.'

However, the Archbishop's name does not appear in the entry for this day in Herschel's visitors' book.

The telescope fell out of use, and was dismantled in 1839, seventeen years after Herschel's death, on the return of John Herschel from South Africa, where he had gone to complete his father's review of the heavens.

The Herschel family celebrated the occasion by holding a party in the tube of the telescope, now laid on the ground. They sang songs specially composed for the occasion:

Merrily, merrily let us all sing,
And make the old telescope rattle and ring . . .

William Herschel's remarkable health and constitution persisted until his later years. He continued his systematic sweeps of the heavens until 1802, when he was sixty-four, and he did not suffer any serious diminution in his strength until 1808, when he was seventy. Thenceforth he could give his telescope only a little of the final polish himself, but he continued for several more years to observe special objects of interest. He made his last observation, on Saturn, with the giant 40-foot telescope in 1815. After 1816 all his letters were written for him by Caroline, but his intellectual work did not cease. In a series of papers from 1811 to 1817, when he was seventy-nine, he outlined a complete theory of how a gaseous nebula might condense into a star or group of stars, with many illustrations drawn from the vast range of nebulae which he had observed. In his eightieth year he published a paper on the relative distances of clusters of stars, and how far telescopes may be expected to reach into space.

Herschel was knighted by the Prince Regent in 1816. Besides receiving the highest honours of the Royal Society

and many other academies, he was elected in 1821 to be the first President of the newly-founded Royal Astronomical Society. He published his important last paper, on new double stars, through the new society.

He died of old age on 25 August 1822, and was buried in Upton Church at Slough. The Provost of Eton, Dr. Goodall, and John Herschel composed his Latin epitaph, containing the famous words: '. . . . *coelorum perrupit claustra* . . . he broke the barriers of the heavens . . .'

REFERENCES

The Herschel Chronicle, by Constance A. Lubbock. Cambridge University Press.

The Herschels and Modern Astronomy, by Agnes M. Clarke. Cassell: 1895.

William Herschel, by J. B. Sidgwick. Faber and Faber.

V

HENRY NORRIS RUSSELL

1877

HERSCHEL discovered much about the arrangements of the stars, but little about their composition, beyond their consisting of matter which obeyed the law of gravitation. Whether they were made of the same sorts of matter as the earth remained unknown.

The first insight into the sorts of material out of which the stars are made came from the application of the discovery that the light from glowing matter contains particular rays which are characteristic for that kind of matter. These particular rays are observed by examining the light with a spectroscope. This instrument separates it into its component rays. If some common salt is heated in a nearly colourless flame such as that of a bunsen burner, it produces an intensely yellow light. When this light is separated into its component rays by a spectroscope, it is found to be unlike sunlight, which splits into the colours of the spectrum. The light from the flame in which common salt is heated consists almost entirely of yellow rays. These are emitted by the sodium, which is one of the two constituents of sodium chloride, the scientific name for common salt. They are, as it were, a label of the element sodium. If sodium is in the hot atmosphere of the sun or stars, it will emit these characteristic rays, and its presence can thereby be detected. The intense yellow light from

some of the discharge-lamps used in street lighting is produced by sending an electric discharge through sodium vapour. This excites the sodium and makes it emit its particular rays.

After the discovery that each of the chemical elements when hot or excited emits particular light rays which are characteristic of it, astronomers attached spectroscopes to their telescopes in order to analyse the light coming from the stars. They at once discovered that it consisted of mixtures of particular rays which were like those emitted by well-known chemical elements on the earth, though with many modifications.

The combination of the spectroscope with the telescope thus led to the discovery that the stars are made of the same kinds of matter as the earth. This was a tremendous extension of the idea of the uniformity of nature, for it is a very striking thing that the millions of nebulae and stars in all the hugeness of the universe should be made of the odd hundred chemical elements known on the earth. It would not have seemed strange if the stars in the depths of space had been made of elements quite different from those known on earth. Why should the materials at the other end of the universe be of the same type as those found here?

The *simplicity* of the universe is continually surprising. It is very fortunate for us, because if the distant parts of the universe were fundamentally different from what it is like on the earth, we would probably not be able to discover much about it.

The development of astronomical telescopes after Herschel required large-scale expensive engineering. This

was undertaken by the Earl of Rosse in Ireland, the father of the famous inventor of the modern steam-turbine, Charles Algernon Parsons. After Rosse, the initiative passed to America, where the large sums of money for building huge telescopes were more easily found, and the atmospheric conditions for using them to good purpose are much better in the clear air of the mountains of California than on the foggy plains of England.

Under these conditions, the American astronomers naturally forged ahead with the collection of information on the composition of the stars. By the beginning of the twentieth century they had compiled an immense amount of data from the spectroscopic examination of thousands of stars. It became necessary to classify and interpret information on the *material* of the stars, as Herschel had classified and interpreted their *arrangement*. The foremost part in carrying out this task, which has provided the basis for the modern theories of the constitution and evolution of the stars, was performed by Henry Norris Russell, the greatest of American astronomers.

As the number of stars is so enormous, the number and variety of stellar spectra is immense. Their classification and interpretation is a work of detailed scholarship, which calls for qualities quite different from those usually associated with American endeavour.

Owing to their history, Americans have been accustomed to approaching activities from the practical rather than the theoretical point of view. The typical conception of the American is of the self-taught practical man who has succeeded by energy and shrewdness. This has been reflected in astronomy, as in other things. Practical

astronomy is very popular; thousands of Americans have their own astronomical telescopes in their back-gardens. The national tradition of technical skill and taste for machinery finds a rewarding field in the making and manipulation of astronomical equipment.

The practical side of American astronomy is better known than its scholastic side, because it was for long the more characteristic and spectacular. It is exemplified by giant telescopes, of which the 200-inch reflector at Mount Palomar is the most famous.

Besides these universally recognized practical characteristics, there has been another less prominent but very important side of American astronomy. This is the academic, which pursues astronomy as a subject of scholarship and theoretical research.

Henry Norris Russell stood at the head of this tradition. His long and very productive life was as completely academic as Edison's was practical, yet it was very influential. Besides his chief work on the constitution of the stars, he made contributions to a very wide range of astronomical problems. He published two hundred and forty-one papers and five books. He had an encyclopaedic knowledge and interest, which made him the chief consultant on astronomy in America. In addition to his own professorship at Princeton, he had close connections with the observatories of Mount Wilson, Lick, Lowell, Harvard and with other great research institutions.

He became the consultant, friend and guide of virtually the whole of American astronomy. He exerted an even greater influence by his stimulating discussions than by his own extensive discoveries. He grasped other people's

problems, as well as his own, with lightning rapidity. He poured out suggestions, criticisms, calculations, and gave innumerable hunches on the directions in which solutions might be found. His advice was widely sought on drawing up programmes of research. He became an informal planning and directive influence on the vast amount of American effort in astronomy.

In addition to his research work and consulting, he contributed a monthly article on astronomy to the *Scientific American* from 1900 . This unsurpassed piece of popularization, which was of the highest quality, virtually educated the American people in astronomy during the first half of the twentieth century.

His experience in popularization probably helped him in writing his masterly textbook on *Astronomy*. This was written in collaboration with his colleagues R. S. Dugan and J. Q. Stewart. It was published and reorientated and revolutionized the teaching of astronomy in America. It was entirely modern and yet perfectly balanced, extremely clear, and of uniform technical level.

He came of long lines of Puritans and Presbyterians on both sides of his family. His mother Eliza Norris was descended from Old Colony Puritans. One of them had fought the delusion of witchcraft, when it was dangerously rampant in Salem, Massachusetts; two others were expelled from the Society of Friends for taking part in Arnold's expedition to Quebec in 1775.

This side of the family engaged in typical New England business. One of them became the skipper and owner of a ship, on which he died in the West Indies of yellow fever. He had a grandson whose wife, Russell's maternal

grandmother, won a mathematics prize in graduating at the Rutgers Female Institute in New York in 1814. This was the first institution founded in that city for the higher education of women. These Norrises, who were interested in the rubber business, lived in Brazil for ten years. While at Para, where Mr. Norris was temporary U.S. Consul, their daughter Eliza was born. After Brazil, the family went to Edinburgh, where they lived for eight years. Eliza Norris was educated there, and attended the special mathematics class for ladies at Edinburgh University (before the university was formally opened to women) and came out easily first.

On his father's side, Russell was descended from a Scottish hand-loom weaver who became an elder of the kirk, and was ruined by the introduction of steam-driven machinery in the industrial revolution. He died in debt, which his children dutifully paid off by strenuous labour. A son emigrated to Nova Scotia, and became a teacher. One of his sons worked his way through college at Halifax, and then went to Princeton to study for the ministry. While there, he met and married Eliza Norris.

The Reverend Alexander Russell was appointed pastor at Oyster Bay, and continued there until his death thirty-three years later. He was a learned theologian, who worked for the revision of the Presbyterian Confession of Faith, in order to remove the polemical expressions inherited from the controversies of the sixteenth century, and give it a modern expression.

Russell's mother was a stern moralist, who judged everyday behaviour by direct comparison with the Ten Commandments. Besides being highly religious and

moral, the Russell family had also the associated habits of economy and carefulness; they were always comfortably off. Russell was brought up with a strong sense of duty, and yet in material comfort. He was educated at home until the age of twelve, and then sent to the Princeton School. After this, he entered Princeton University, at a period when more than half of the staff were active members of the church, and attendance at service was compulsory. He was quite at home in this atmosphere. He said in his later years that he had enjoyed a happy and rather sheltered life, and that he had found Princeton the 'happiest of ivory towers'.

There could scarcely have been a greater contrast between this life and that of the American pioneers, yet he was not out of touch with business people. A number of city men used to make Oyster Bay on the coast their summer headquarters. Russell met his future wife, Lucy Mary Cole, in the home of one of them. They were married in 1908. The Russells had four children, all of whom were good at mathematics.

Russell was a passionate admirer of Theodore Roosevelt, whom he regarded as the last Puritan. He believed that Theodore Roosevelt's power arose from his ability for making Americans conscious of sin.

Russell was a dazzlingly successful student. He graduated in 1897 with the highest standing ever attained by a Princeton student. He had the family skill in mathematics, with a special gift for mental calculation, and a quite exceptional memory. He knew the pages of figures in tables of logarithms by heart. He could answer questions with extraordinary speed and well-ordered comprehen-

siveness. He had a tall lean figure, and a brow that overshadowed his face. His appetite for knowledge and work was voracious. His extraordinary memory and powers of graphic expression made him an outstanding lecturer; he often spoke for three or four hours, holding his students spellbound. Experts could ring him up on the telephone for recondite astronomical information, such as the data on all stars which were known to be triple. He could answer such questions without consulting works of reference. He could give perfect extempore accounts of astronomical topics casually raised in social conversation and at parties.

After his brilliant graduation he was awarded a mathematics fellowship, and engaged in research for his doctorate under the eminent Princeton astronomer C. A. Young.

He had been interested in astronomy from his childhood, and was able to remember his parents showing him the transit of Venus in 1882, when he was five years old. Under Young's stimulus he started his fruitful career of discovery. Before receiving his doctorate in 1900, he had already published papers on five different topics. The first two were in 1898, on a new graphical method for working out the orbit of binary stars, in which the pair are revolving round a common centre of gravity; and a method of calculating the orbits of certain minor planets. In the following year he published papers on the perturbation of the minor planet Eros by Mars; on the measurement of the diameter of Jupiter; and on the calculation of the densities of certain variable stars.

Russell overworked himself in this period. He had a

nervous breakdown, and returned home for two years' rest. In 1902 he went to Cambridge in England. He entered King's College, and worked in the Cavendish Laboratory at physics in the great days of J. J. Thomson. He acquired a thorough training in modern physics as well as in mathematics. He regarded his time at King's College as his introduction to the greater world. The Anglo-Catholics, Agnostics and Tories he found there surprised his Presbyterian notions by proving in a number of cases to be fine people.

After working in the Cavendish Laboratory he was enabled by the Carnegie Institution of Washington to work as a research assistant in the Cambridge Astronomical Observatory. He started work on the measurement of the distances of stars by photographic methods. Shortly afterwards his mother died. He was deeply attached to her, and felt the loss as the severest personal blow he ever suffered. He was greatly helped in this difficult period by his Cambridge friend and collaborator, the English astronomer A. R. Hinks, who not only took him into his home and looked after him, but completed his observations, and forwarded the material to him for working out, after he had returned to America.

After recovering from this crisis, he was appointed an instructor in astronomy at Princeton in 1905. Thenceforth his stream of papers flowed on for more than fifty years. His last paper, published in his eightieth year, and the year of his death, was, like one of his first in 1898, on the subject of variable stars.

Russell was promoted to the professorship of astronomy in 1911. He became director of the University

Observatory, and in research professor. He retired from university work, but not from research.

Though Russell's researches on the planets and the solar system formed only a small part of his total work, they were in themselves very considerable. In his early paper on Venus, published in 1898, he showed that observations indicated that the cusps, or corners, were longer than they would be if Venus had no atmosphere. He calculated from the size of the increase in length that Venus must have an atmosphere which was more than one-third as dense and extensive as that of the earth.

Nine years later, in 1907, he observed Venus when it appeared as a luminous ring; a phenomenon subsequently photographed by E. C. Slipher.

About the year 1916 he made a thorough investigation of the stellar magnitude of the sun, moon, planets, satellites and minor planets, that is, their magnitude as they appear to the naked eye in comparison with a standard star. He also estimated the stellar magnitude of the earth as it would appear to an observer on the sun.

Shortly after the First World War he published an investigation of the theory of the capture of comets by the planets. He showed that nearly all of the comets which revolved round the sun periodically must have been captured by Jupiter while passing near to it from outer space. He suggested that two groups of comets, which have periods of return of about 406 and 775 years respectively, might have been captured by remote planets that have not yet been discovered.

Russell continued to work on the gravitational theory

of pairs of stars, which he had started in his earliest papers. He devoted much effort to the simplification of the calculations from the observed data. One of the characteristics of his work was systematic search for the easiest and most labour-saving way of conducting an investigation. Some of his critics said that he was prepared to spend more time on finding an elegant short cut than the long cut would have taken.

He summarized and analysed all the direct evidence on the masses of stars which can be deduced from the gravitational behaviour of pairs revolving round a common centre of gravity. He concluded that there were only about two dozen visible pairs from which reliable values could be deduced, and about as many more variable stars of the eclipsing type, discovered by spectrographic means.

He analysed the mechanics of what happens when a mass of gas separates into two components by a process of fission. As the components revolve around a common centre of gravity they exert a mutual tidal action, which gradually causes the distance between them to increase. He discussed what would happen if fission should subsequently occur in the smaller component, or in both components. He compared his results with what is actually observed in the known pairs of revolving stars, and in the triple and multiple stars. He concluded that these stars are most probably formed by the successive fission of masses of gas, which have broken apart through an increasing rate of rotation, due to contraction in size following on the loss of energy in the course of radiation, or shining.

Russell published his first investigation on pairs of eclipsing stars in 1899, and his last . He deduced from the period and duration of the variation in the light from such a pair that the stars must be much less dense than the sun, with an average density of less than a quarter of that of the sun, though the core might be much denser and the outer atmosphere much less dense. He worked out in detail, and reduced to tabular form, the general methods for determining from observational data the features of any pair of eclipsing stars. He started with the simplest case, in which each star is spherical and the orbits are circular. Then he went on to increasingly complex cases, in which the stars may be pulled into flattened spheres, or ellipsoids, through distortion of their material by mutual gravitational attraction.

In addition, he worked out the case when such distorted stars are moving, not in simple circles, but in elliptical orbits. His most famous pupil Harlow Shapley collaborated with him in much of this work.

Russell made a complete analysis of 2,111 observations of six eclipsing pairs, and succeeded in explaining what both the visual and photographic observations implied in all six cases. He showed that when pairs of revolving stars have a short period, the densities of the cores of the two components are from 40 to 400 times the average density.

Russell's last major paper on eclipsing stars was published, when he was seventy-five years old. With the collaboration of J. E. Merrill he worked out a complete method for calculating the characteristics of a system of eclipsing stars from observations of the most

modern kind. Russell was persuaded by Shapley to write his very last paper, published in the year of his death, by sending him data on the light variations in some eclipsing pairs in the Magellanic Clouds, which are outside our own local galaxy of stars. Shapley thought that it would be as well to be sure that the laws of gravitation are the same in those other galaxies as in our own, and to make sure that stars there are generally similar to those in our galaxy. Russell showed in this final paper that the densities of the stars in these eclipsing pairs in other galaxies were indeed similar to those in our own galaxy.

The most important part of Russell's many-sided work started from his measurements of the distances of stars, which he began at Cambridge. When a star's distance is known, its absolute magnitude can be deduced from its apparent magnitude. By measuring the distance of fifty-five stars, Russell succeeded in deducing their absolute magnitude. He found that there were two very different kinds of red stars, one of very great and the other of small magnitude, or candle-power. He interpreted the red stars of great magnitude as being huge volumes of relatively cool gas, in process of condensation to form ordinary stars, while the red stars of small magnitude were old stars that were dying down because of their age and having radiated so much energy. In 1913 he expressed these conclusions in a famous diagram. He showed that if the absolute magnitude of a star is plotted against its colour, or spectral class, the vast majority of its class lie along a straight line, within a narrow channel.

The basic data in Russell's diagram had been discovered some seven years earlier by the Danish astronomer

Hertzsprung, from an examination of the work of the American astronomer Antonia C. Maury. She had been classifying the spectra of stars, and she suggested that the variations between them were due to the different stages of their evolution. In general, the proper motion of a star, the speed at which it appears to drift from its position in the sky, is a measure of the star's distance. If the star is very distant its proper motion is very small.

Hertzsprung estimated the distance of Miss Maury's stars from their proper motions. He then compared their apparent magnitude with their distance, and thus calculated their absolute magnitude. He had found that red stars were of two types, very luminous ones which he called 'giants' and faint ones which he called 'dwarfs'. He was referring not to their physical size, but to their absolute magnitude, or candle-power.

Hertzsprung had published this work in a German journal of scientific photography, where it remained apparently unread by astronomers until Russell had independently re-discovered the basic ideas by another method. This incident is a striking illustration of how the progress of science depends not only on making discoveries, but also on making them in an environment in which they will be recognized and appreciated.

When Russell had made his discoveries, he was able, as an American astronomer at the centre of American astronomy, to secure immediate appreciation of them, whereas Hertzsprung's results, obtained from American material by work in Europe and published in a non-astronomical journal in the German language, was for long unnoticed.

The discoveries of Russell and Hertzsprung, which were so strikingly expressed in Russell's diagram, now universally known as the Russell-Hertzsprung diagram, have been the foundation of subsequent research on the constitution and evolution of the stars.

Russell sought for the explanation of the differences between the 'giants' and the 'dwarfs' in terms of all of their physical characteristics. He used the calculations of himself and Shapley on eclipsing stars to determine their physical size and properties, and he showed that in general the 'giants' were not only gigantic in candle-power but also in diameter, while the 'dwarfs' besides being small in candle-power were small in diameter.

Russell investigated in detail the changes in temperature, density, brightness in colour, or spectrum, that a star would undergo with the passage of time, and he related these properties with the mass, angular momentum and chemical composition. He incorporated these in a general theory of the evolution of the stars, which guided research in this subject for twenty years, and brought it to the threshold of the modern period by posing the question: 'What is it that keeps the stars shining?' Russell lived to see the answer found by his successors: atomic energy.

The explanation of the evolution of the stars depended on the application of the new discoveries in physics to all of the immense variety of stars. Russell pursued this work with intense energy. Besides acquiring a very wide knowledge of the observed spectra of the stars, so that he could have an insight into all of the many kinds, he engaged in laboratory and theoretical researches in pure spectroscopy to sharpen his physical knowledge as an

instrument for astronomical research. In the course of this work he made a number of first-class contributions to pure physics, discovering important new features in the spectra of elements, and explaining them in terms of the newly-developed quantum theory. He paid special attention to the spectra of elements such as calcium, which are particularly important in the sun and stars.

Russell revelled in the detailed complexity of spectra. He approached them in the spirit of solving 'a glorified cross-word puzzle'. He had more than twenty distinguished collaborators in this work, and he inspired many others. He classified in detail, as it were, the whole range of materials out of which stars are made, and thus provided everyone, including himself, with the data from which theories of stellar evolution can be deduced.

When the Indian physicist M. N. Saha published his theory of the ionization or electrification of gases by heat, Russell immediately applied it to the theory of the atmosphere of the sun and stars. He showed that the pressure of the gases in the sun's photosphere (the visible disc of the sun, on which its atmosphere rests) must be less than one-hundredth of the earth's atmosphere, as the spectrum lines from it are substantially the same as those obtained in an ordinary vacuum in a laboratory experiment.

He deduced from the sun's spectrum the various elements in its atmosphere. He tabulated 56, and estimated their relative abundance. He proved that there was very much more hydrogen present than any other element. This extremely important discovery has since been extended to the stars and the whole universe. It is the foundation of some of the most modern theories of the origin of the

universe. For instance, in the theory of the continuous creation of matter, it is supposed that matter is continuously coming into existence in the form of hydrogen atoms. These provide both the material and the motive force by which the evolution of the universe proceeds.

Russell's estimate of the constitution of the sun became known as the 'Russell mixture'. The theorists made theoretical models of various sizes and kinds out of this 'mixture', and then calculated how they would behave. The results were compared with what is actually observed in the sun and stars. Modifications were then made in order to get a better fit, so that ultimately theoretical models were produced whose behaviour could be shown by calculation to resemble closely what is actually observed.

Russell made the atmospheres of the sun and stars almost as familiar as the atmosphere of the earth, by his detailed research on every aspect of their physical properties, their temperatures, pressures, densities and opacities.

Together with this main work on the constitution and evolution of the stars, he continued to contribute to a wide range of fundamental subjects. He discussed the origin of the solar system, which he was disposed to think was due to the interference of a passing star with a binary, or pair of stars. He supposed that the passing star had collided with the smaller of the pair.

He made the classical deduction of the age of the earth from its content of radioactivity. He worked out in 1921 how old the crust of the earth would be if it had originally been made entirely of uranium. Then he worked out the

age if the original content of uranium had been only fractional. He concluded that the crust is between two and eight thousand million years old. Today, the estimate is between four and six thousand million years.

While Russell's immense scientific energy was directed almost entirely to astronomy he could, with characteristic versatility, quickly apply his remarkable aptitudes to any problem. He worked for some time during the First World War in aircraft research, and subsequently published a paper on the navigation of aircraft. In the course of this work he made observations at a height of 16,000 feet, and at speeds of 105 miles an hour, when aircraft and flying conditions were still rather primitive. As a result of this research, he made various practical suggestions on instruments and methods, and characteristically worked out the most efficient and quickest ways of using them.

Russell's tireless mind left him with energy to pursue many other things besides astronomy. He was interested in poetry, such as that of Coventry Patmore, which deals with the qualities of existence:

Wonder and beauty our own courtiers are
Pressing to meet our gaze
And out of obvious ways
Ne'er wandering far.

Russell liked to point out that while, as Patmore says, art deals with familiar things, it is the special province of science to expand the human imagination, and thus reveal new wonders which otherwise would have remained outside human experience. He regarded the ever deeper and more comprehensive views gained by astronomy into

the nature of the universe as one of the supreme examples of the service of science to the expansion of the human imagination and spirit.

He was interested in natural history, and enjoyed searching for rare plants in the neighbourhood of Princeton. Harlow Shapley has described how, as a somewhat uncouth youth from Missouri (Shapley started life as a journalist), Russell at first eyed him doubtfully. After a period of uncertain relationship, Shapley at last realized that he had been approved, when, one day 'Russell very privately told me a deep secret; that is, he told me just where in the woods four miles north of Princeton I could find the rare and precious fringed gentian. I had indeed made good. . . .

Russell travelled extensively. He knew the Old World from the North Cape to the Valley of the Nile. He was interested in archaeology and the ancient Egyptian monuments. He applied his knowledge of astronomy to the determination of a planetary date for Chaucer's Troilus. He was particularly devoted to children, and children of astronomers all over the world, even many now grandparents themselves, still look back on him with devotion, and remember the charming animals he used to make for them out of folded paper.

The Russell family attended scrupulously to matters of doctrine. After he was married, he and his wife, who was an Episcopalian, faithfully kept to their respective creeds. His devotion to religion remained active and deep throughout his life; he became an elder in his church.

He gave sustained attention to the problem of the relations between science and religion, and he tried to find

in some of the modern developments of mathematics and physics explanations of fundamental difficulties in theology. He developed his arguments in a course of Terry Lectures on *Fate and Freedom*, delivered at Yale University in 1925. He believed that the mechanistic theory of nature, including human nature, was not incompatible with religion, but on the contrary was capable of rendering it important services. The scientist was continually forced to think new thoughts, and to welcome the supersession of his own work. The beautiful picture of the heavens, which was presented to the ancient imagination as a crystal vault lit with starry lamps, had been superseded by the awe-inspiring grandeur of the void of space sown with stars.

Russell believed that the great service of science to religion was to show that there are new ways of conceiving things, and that therefore it should be possible to conceive entirely new ways of looking at the problems of life and existence, which would resolve the contradictions that perplex the human soul. For instance, Cantor's mathematical theory of transfinite numbers, in which the part is equal to the whole, throws light on the nature of infinity and makes it easier to understand the difference between God and Christ.

He believed that consideration of notions such as pressure and temperature, which introduce ideas of different levels of interpretation and statistical conceptions, made it easier to understand the relations between freedom and responsibility. Pressure is a real and concrete notion, but it depends on the collective action of a large number of individual atoms. It becomes imprecise and loses its meaning when used to describe the effects of a single atom

enclosed in a vessel. He argued that notions such as 'sure', 'solid' and 'everlasting' had a similar sort of conditional reality, so that one could fairly conclude that freedom is at least as sure as sunrise, as solid as rock, and as immovable as the everlasting hills. He contended that this degree of certainty was quite sufficient to satisfy the just demands of man.

He thought that the strongest ground for belief in immortality is that God gives mankind more than it deserves or desires. It seemed to him that this was confirmed by the infinite richness, variety and ingenuity of nature, which he had learned to appreciate in a lifetime of study.

Russell combined a passionate devotion to religion with a passionate belief in mechanical determinism. This must seem to many a contradiction. There was a similar apparent contradiction between his Christian optimism and his profound admiration for the most pessimistic passages in the *Apocrypha*. He quoted with the deepest feeling:

> All things come alike to all; there is one event to the righteous and to the wicked, to the good and clean and to the unclean . . . the heart of the sons of men is full of evil, and madness is in their heart while they live, and after that they go to the dead. . . . For the living know that they shall die; but the dead know not anything, neither have they any more a reward; for the memory of them is forgotten; and their envy is now perished; neither have they any more a portion forever in anything that is done under the sun. . . . Whatsoever thy hand findeth to do, do it with thy might; for there is no work,

> nor knowledge, nor device, nor wisdom, in the grave, whither thou goest. . . .

Undoubtedly, the last of these passages could have provided the most appropriate epitaph for Russell's life; no one strove more than he to do the work his hand found to do.

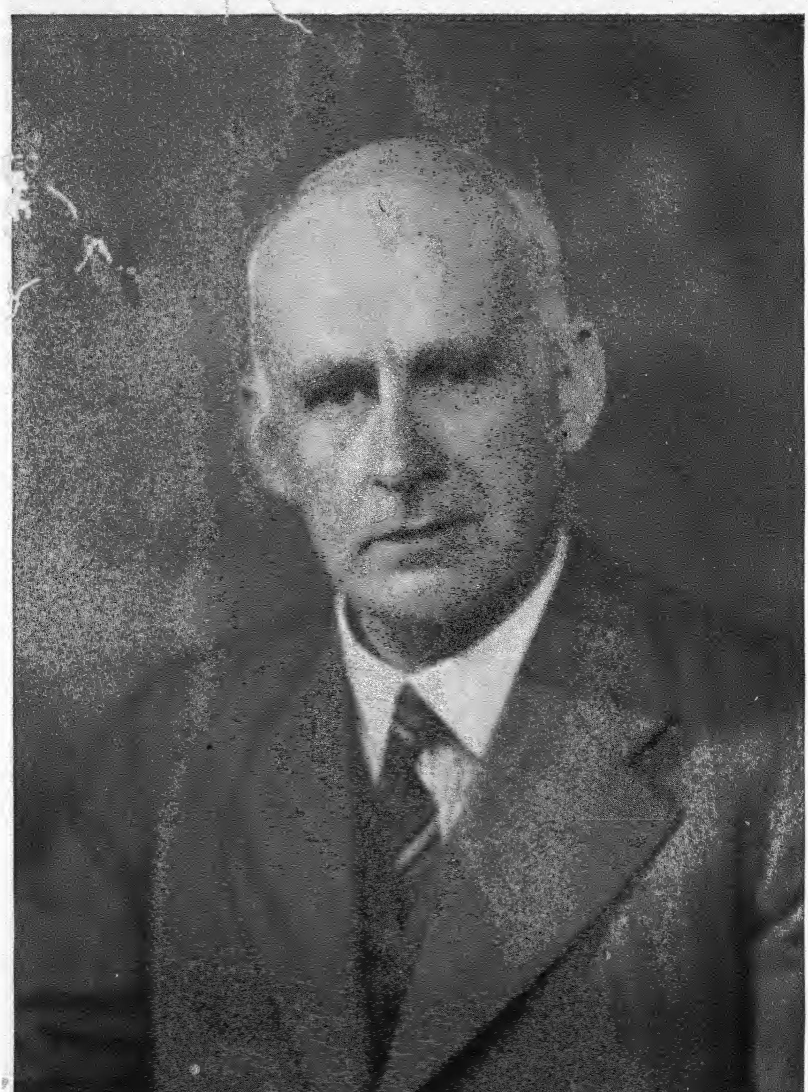
As an astronomer, Russell belonged to the ranks of the supreme technicians; to the Tycho Brahes rather than the Keplers. He contributed effectively to a multitude of problems, and inspired an immense range of effort beyond his own. He did not produce a great general theory, like Kepler's laws of planetary motion. He behaved rather as if he could not allow his powerful mind to linger on any general problem of principle, but was impelled with all his mental force to attack one particular problem after another. The result of his life's work was an immense mass of particular discoveries and a great impulse to the research of others. At least thirty-six notable American astronomers collaborated with him in joint papers.

It may be that the characteristics of his work were moulded by his Presbyterian and Puritan background and conscience. He felt driven on to work and work, but could never allow himself to give a free rein to his strong imagination. The American civilization of his time encouraged activity rather than meditation. Russell was the supreme expression of the national spirit in the realm of astronomy. He is one of the most significant figures in the history of American science.

Russell's health began to fail in his last years, though his mind remained active to the end. He died at Princeton, after a long illness, on 18 February.

Photo: George Karger

HENRY NORRIS RUSSELL



ARTHUR STANLEY EDDINGTON

Russell received most of the distinctions of the astronomical world, and was a leading figure in the International Astronomical Union. He received the Gold Medal of the Royal Astronomical Society of London, and six other medals from leading societies of the world. He received honorary degrees from six universities. He was an honorary fellow of King's College, Cambridge. He was a member of the National Academy of Sciences of ~~the~~ U.S., and served as President of the American Astronomical Society, and other American societies. He was a foreign member of the Royal Society of London, and the Academies of Science of France, Belgium and Italy.

REFERENCES

Henry Norris Russell, by F. J. M. Stratton. Biographical memoirs of Fellows of the Royal Society. Vol. 3. The Royal Society.

Henry Norris Russell, by Harlow Shapley. Biographical Memoirs of the National Academy of Sciences of the U.S. Vol. XXXII. Columbia University Press.

Henry Norris Russell: *Thirteen Americans.* Their Spiritual Autobiography. Edited by Louis Finkelstein. Institute of Religious and Social Studies. New York.

Fate and Freedom, by H. N. Russell. Yale University Press.

VI

ARTHUR STANLEY EDDINGTON

1882

TWENTIETH-CENTURY ideas of how the stars have evolved have been derived from discoveries of connections between their various characteristics, of which the relation between candle-power and colour, discovered by Russell and Hertzsprung, has been particularly fruitful. The attempt to explain this relation has been the main starting-point for the development of modern knowledge of the evolution of the stars. The Russell-Hertzsprung discovery opened the first page of the new book of ideas on stellar evolution.

The first major author in the modern book on the evolution of the stars is Eddington, who, by virtue of his achievements, became the greatest astronomer of his generation. Eddington was the first to apply on a big scale the new knowledge of atomic physics, gained in about a dozen years near the beginning of the twentieth century, from J. J. Thomson's discovery of the electron in 1897 to Rutherford's discovery of the nuclear structure of the atom in 1911.

Before this time, the atom had been thought of as a hard impenetrable ball. Afterwards it was conceived as a kind of solar system, consisting of a hard impenetrable nucleus surrounded by revolving electrons, like the sun surrounded by revolving planets. Later on, it was discovered that the

nucleus itself had a structure, which was proved by Rutherford when he first disintegrated an atomic nucleus in 1919.

The science of the atom as a whole, of the nucleus surrounded by its revolving electrons, is generally called atomic physics. Since the discovery that the nucleus of the atom also has a structure, which can be broken up and put together again, a new science of the nuclei of atoms has grown up. It is called nuclear physics, and has been developed especially in connection with the release of the energy of the atomic nucleus, in atomic reactors and power plants.

Eddington was the master of the application of atomic physics to the explanation of the stars. He was the predecessor of the present generation of theoretical astronomers, who, pushing on from the application of atomic physics, are now investigating the evolution of the stars with the aid of the new nuclear physics.

Arthur Stanley Eddington was born at Kendal in Westmorland on 28 December 1882. He came of a Quaker family, both of his parents being descendants of lines of Quakers. On his father's side they were Somerset farmers, and his mother, Sarah Ann Shout, belonged to a family of Yorkshire Quakers. Her family name was probably of Dutch origin, derived from Schouten.

Eddington's father, Arthur Henry Eddington, was a talented schoolmaster, who became the head and owner of Stramongate School at Kendal, the Quaker school where the famous Quaker scientist, John Dalton, had once taught. Arthur Henry Eddington had been educated at Friends' schools at Sidcot and Ackworth. He studied

philosophy at Heidelberg in 1874–75 in the time of Kuno Fischer, the eminent German philosopher who was particularly interested in Francis Bacon. He graduated at London University, and was appointed a master at Ackworth. He became head of Stramongate in 1878. His ability and character soon earned him general esteem. His first child, his daughter Winifred, was born in the year that he settled in Kendal, and his second, Arthur Stanley, four years later. Then, before his son was two years old, Arthur Henry Eddington died in a typhoid epidemic which struck the school and town in 1884. He was tragically deprived of the opportunity of providing his son with the support and guidance which he was so well qualified to give, but he contributed his part in endowing him with ability and character.

His young widow with her two infant children went to live with the Somerset Eddingtons, and settled with her mother-in-law in Weston-super-Mare. She had been left with little means, so circumstances as well as tradition inclined her children to the inexpensive pleasures of the mind. Eddington remained simple in his taste throughout his life. He very rarely drank alcohol, and his favourite exercise was solitary cycling. He not infrequently cycled more than 100 miles in a day, and he kept a detailed record of his trips, during which he covered most of the main roads in England. In the last year of his life, when he was sixty-one, he made many long rides, one of 83 miles in a day. His longest recorded ride was when on one day he cycled the 122 miles from Doncaster to Cambridge.

Eddington remained a bachelor. He became an inveterate pipe-smoker, and relaxed by reading detective stories

and solving cross-word puzzles, and playing an occasional game of golf.

The home of the Eddington family continued to be at Weston-super-Mare until 1914. Eddington was reared in this quiet watering-place, near the Mendip Hills, Cheddar Gorge, Wells and Glastonbury, in a region rich in history and legend from Roman, Arthurian and medieval times. His early environment probably strengthened his tendency to detachment and imaginative reverie, and encouraged the poetic feeling for words and ideas which became an outstanding quality in his books on the exposition of science.

Eddington showed an exceptional ability in arithmetic, and an interest in big numbers, at a very early age. He learned the 24 x 24 multiplication table before he could read. He combined his ability in arithmetic with an interest in the stars. One of his boyhood pleasures, at the age of four, was to be taken on to the promenade at Weston on fine evenings, when he would try to count the stars. His family thought this may have strained his eyes. When he was twelve it became necessary for him to wear glasses. Eddington said he was first attracted to astronomy when he was six years old, by its big numbers.

His education was begun at home. He went to a small preparatory school, and then to Brynmelyn School in Weston, which he attended from 1893–98. One of the founders of this excellent school had been a school-fellow of Eddington's father at Sidcot and Ackworth. It was a boarding school, in a handsome building with a fine view over the sea. Eddington was allowed to attend it as a day-boy. It had good teachers of natural history and

mathematics, and a particularly good teacher of English, the Rev. A. Allen Brockington. Eddington described nearly forty years later how Mr. Brockington had transformed the usually wearisome hours of English lessons into a joy and a revelation, and had not only opened the door on English literature to his pupils, but in his enthusiasm swept them through with him.

He began telescopic observations of the sky when he was ten years old, with a three-inch telescope lent to him by his headmaster. In his home he used to announce that he would lecture in the attic at a given hour on some astronomical topic such as Mars or Jupiter, and he wrote astronomical essays for the school journal.

When he was in his teens, Sir Robert Ball, one of the Cambridge professors of astronomy, gave a popular lecture in Weston-super-Mare. Eddington was taken to hear him, and his mathematics master introduced him to Ball, who told him that the career of an astronomer was hard, and that there were few openings. A score of years later, Eddington succeeded Ball as director of the Cambridge Astronomical Observatory.

He was a very successful schoolboy. Besides gaining a first-class with distinction in mathematics in the Cambridge Junior Local examination when he was fourteen, he won a Somerset County Council scholarship of £60 a year for three years when he was fifteen. He accomplished all this easily, without interfering with normal interests. He was a member of the First Eleven for both cricket and football. Many years afterwards, Eddington showed how the complete score-card of a cricket match could be reconstructed from a few data of the final result,

as an example of the method of inference, by which the conditions inside a star can be inferred from the final conditions observed on its surface.

With his scholarship he was able to go to Owens' College at Manchester. As he was still under sixteen, the regulations had to be relaxed in order to admit him. He resided at Dalton Hall, whose principal had been an assistant master under Eddington's father at Kendal. When Eddington first arrived at Dalton Hall, he was still virtually a schoolboy. Unlike the other students, who were wearing adult attire and bowler hats, Eddington appeared in short trousers and a cloth cap.

His principal found him a most modest and gentlemanly boy, whose character had not been at all spoilt by the superiority of his mental powers. He was inclined to be solitary, but this had not prevented him from making friends.

He spent the first year on a general course of study, covering work which most boys did at school; in it, he made progress in Greek. Then he specialized in physics under Schuster. He attended Horace Lamb's lectures on mathematics, and was much influenced by them. There are signs in his work that he was also influenced by the great professor of engineering, Osborne Reynolds. Eddington could visualize the processes of nature as if they were working machinery. This concrete imagination, which is the engineer's greatest gift, enabled him to visualize the star as a heat-engine, and thus deduce how it works. His mathematical analysis of what happens in a star was not simply rows of symbols. He could see in his mind's eye what was going on inside the star.

In the examination of his second year he was a long way in front of all other candidates in mathematics. In the mechanics paper he gained full marks, and he was also top in Latin and English History. He won additional scholarships, and then, in his last year at Manchester, he sat for a scholarship at Trinity College, and was awarded a minor scholarship for natural science in 1901.

His final year at Manchester was an exceptionally brilliant one. It included J. W. Nicholson, who was the first to apply the quantum theory to the atom, before Niels Bohr had published his famous work; Petavel, who became director of the National Physical Laboratory, and G. C. Simpson, the future director of the Meteorological Office. Eddington was younger than all these, but he was easily first in the final honours examination in physics.

He entered Trinity College in 1902. It is said that after he arrived he found that he was expected to play a game, called the Mathematical Tripos Examination. He decided to play it for all he was worth, and he duly came out first, or Senior Wrangler, as it was then called, in 1904. No other candidate was ever Senior Wrangler in less than three years. In the previous year he sat for a London degree by the way, and obtained a first-class in mathematics and a third-class in physics. He was in the midst of his preparation for the Cambridge contest.

The particular kind of training for competition in the Cambridge mathematical examination of Eddington's day laid great stress on skill in solving problems, rather than on systematic mathematical thought. It laid a deep impress on Eddington's future work, as it had done on a great deal of the British contribution to physics. His

greatest achievements were in the solution of the concrete problems of the constitution of the star, rather than in developments of pure theory, such as relativity and quantum theory. Among his mathematics teachers were E. W. Barnes, who became Bishop of Birmingham, A. N. Whitehead, the famous philosopher, and E. T. Whittaker, the mathematician who was at one time Astronomer Royal of Ireland.

After his brilliant graduation, he accepted a pleasant tutoring engagement in Ireland during the long vacation, where he was able to enjoy tennis and fishing, besides long walks in the beautiful country. When he returned to Cambridge in the autumn, and started looking for a permanent career, he had no difficulty in securing plenty of good pupils.

He began research in applied mathematics and in experimental physics, neither of which led to immediate results. He started his experimental research in the Cavendish Laboratory, on the speed with which electrons are emitted from hot bodies, the phenomenon on which the action of the radio valve depends. He did not find working conditions in the Laboratory easy, and he soon dropped this work. E. W. Barnes and other influential men at Trinity College tried to persuade him to take up engineering to qualify himself for a college lecturership in this subject, and he assisted for a time in teaching engineering students.

Eddington seems at this time to have intended to become a physicist. Then the position of Chief Assistant at Greenwich Observatory fell vacant, and some of Eddington's teachers advised him to apply for it, which he was

not inclined to do. Largely through the influence of Whittaker, it was offered to him. The offer of the post changed his mind, and he accepted it.

Eddington was in Cambridge during the General Election of 1906. He shared in the enthusiasm for the Liberal victory of that year, and remained a convinced Liberal for the rest of his life. He always followed public affairs, though he did not take part in them.

In various ways, Eddington belonged very definitely to the Edwardian period in English history. He won and enjoyed the opportunities it gave to a small number of men of exceptional ability for a highly cultivated life of intellectual activity. The pre-eminent example of this cultural development was at Trinity College, with its galaxy of scientists, mathematicians and philosophers of the first rank, who were able to use their powerful minds for entertainment as well as analysis. Bertrand Russell has described how he and Eddington used to banter each other with scientific questions. One day Eddington told him that the universe was expanding so rapidly that it would soon be impossible for it to be controlled by a dictator, because his orders sent out with the speed of light would nevertheless not be travelling fast enough to reach the most distant parts. Russell immediately asked, if this was so, how God supervised what was going on in those distant parts. Eddington replied that this question did not lie within the province of the physicist.

Eddington belonged to a serene, intellectually aristocratic society which lived above the events of ordinary life, though knowing about them. He matured in an era which came to an end in the First World War. He had an indi-

vidual outlook which was different from that of most scientists after this war, and doubly different from that of scientists after the Second World War.

Eddington started work at Greenwich early in 1906. He quickly mastered the routine of practical astronomy, and trained himself to be an accurate observer. Though he became famous as a theorist, he was a thoroughly competent practical astronomer. This practical training and sense probably helped to guide his intuition, or power of foreseeing the direction in which the solutions of problems were to be found, which was such a striking feature of his genius.

He still attempted some research in physics, and worked on the theory of electrons, but without much success. Within a few weeks, however, he had found a major subject for astronomical research. The Dutch astronomer Kapteyn had recently made important discoveries about the movement of the stars, a subject which had been founded by Halley and Herschel. Kapteyn had shown that the stars do not drift at random, but could be sorted into two streams. From this, it became possible to make deductions about the shape and motion of the Galaxy our local island universe.

Eddington's first communication to the Royal Astronomical Society was on this subject. He also wrote a thesis on it for a fellowship at Trinity College, and submitted a paper on the same topic for the chief scientific prize at Cambridge: Smith's Prize; he won both his fellowship and the prize. After this he went to Holland for a holiday and called on Kapteyn.

Eddington was sent to Malta in 1909 to take part in the

redetermination of the longitude of an observation station on the island. He gained experience on how such expeditions should be carried out, which later enabled him to make practical observations which were of immense scientific importance. He thoroughly enjoyed the sea voyage to Malta, promenading on the deck and reading *Tristram Shandy* and *Don Quixote*, and preparing lectures.

Later in 1909, he was sounded on whether he would be prepared to accept a chair of theoretical physics at Manchester. He decided not to entertain the proposal as he did not wish to give up astronomy, and doubted whether he would succeed in that field. If he had accepted, he would have become the colleague of Rutherford, at the time when Rutherford discovered the nucleus of the atom, and he would have had the opportunity to fulfil in physics the role that was subsequently performed by Niels Bohr. In the latter part of his career, Eddington returned more and more to the problems of theoretical physics, but this later work has not commanded much acceptance. His early feeling that his genius did not lie in that direction seems to have been sound.

His administrative ability was recognized by his appointments as secretary of the Physical Sciences section of the British Association, and Secretary of the Royal Astronomical Society.

He was much helped by the succession of Sir Frank Dyson as Astronomer-Royal. Dyson was a charming and modest Yorkshireman who combined high intellectual gifts with sociability and native practical sense. He could handle magnificently those situations in which Eddington

was hindered by shyness and reserve. Eddington became deeply attached to him.

Under Dyson's direction, Eddington became the leader of an expedition to Brazil in 1912, to observe an eclipse of the sun. The party was unable to make any observations, owing to continuous rain, but Eddington had still further extended his experience in a type of work in which he was later to achieve momentous results.

Just after this, the Plumian chair of astronomy at Cambridge became vacant through the death of G. H. Darwin, one of Charles Darwin's sons, who had made important contributions to the mechanics of stars, and had investigated the conditions under which rotating stars may fly apart through centrifugal forces; it was supposed that many of the pairs of stars seen to revolve around a common centre must have been formed in this way.

Darwin had had a particularly brilliant pupil, James Hopwood Jeans, who had extended his results. Jeans was five years senior to Eddington, and was already a professor at Princeton in America. He no doubt expected to be elected as his master's successor, but the electors chose the younger man. Eddington was elected to the Plumian Chair in 1913. He was only thirty years old, and not yet a fellow of the Royal Society. One of the factors that secured his election in preference to Jeans was his experience as a practical astronomer. It was anticipated that the directorship of the University Observatory would soon become vacant, which indeed occurred through the death of Sir Robert Ball in 1914, and that it would be necessary to draw up a new programme of practical work.

Jeans showed a feeling of strong rivalry towards

Eddington, and Eddington in his quiet determined way more than held up his own end. During the next thirty years meetings of the Royal Astronomical Society were enlivened by fierce scientific arguments between these intellectual titans, which were listened to with instruction and glee by ordinary astronomers. After Eddington published his popular book on *Stars and Atoms*, which had a large sale, and was translated into ten languages, Rutherford once remarked that Jeans had said to him: 'That fellow Eddington has written a book which has sold fifty thousand copies; I shall write one which will sell a hundred thousand!' 'and,' Rutherford added, 'he did!' This is one account of how Jeans came to write his best-seller: *The Mysterious Universe*.

Eddington summarized the main researches he carried out while at Greenwich in his first book: *Stellar Movements and the Structure of the Universe*. He analysed the data for many more stars, and discussed various types of universe that might be deduced from them. He devised improved methods for deducing the motions of the stars from the observational data, and invented diagrams which depicted the distributions of stars in a striking way. These diagrams, because of their appearance, came to be known as 'rabbits'.

Eddington said in this book that he had been engaged in studying 'the stars as a society'. He had analysed the common movements of stars in a group, and had ignored their individual particularities. He had excluded from consideration their individual physical characteristics. He concluded that his research in stellar motions indicated that it was possible 'to glimpse the outline of some vast

combination which unites even the farthest stars into an organized system'.

He settled in Cambridge as Plumian Professor in 1913, and was elected a fellow of the Royal Society in the following year. Thenceforth, he changed his main line of work, from the group-features of stars to their individual physical characteristics. Many factors impelled him in this direction. In his studies of the motions of stars he had learned that stars of certain physical types tended to move with high speeds. Then, in 1913, the Russell-Hertzsprung diagram, showing that the candle-power of stars is simply related to their physical properties, was published. This relation was just sufficiently simple and clear-cut to raise the hope that it should be possible to do more than give a merely descriptive account of the characteristics of stars in terms of the physical properties of matter, and it suggested that it should be possible to deduce some at least of these characteristics by exact calculation. It inspired the hope that it might be possible to work out the properties of a star as a machine, and discover the nature of the materials of which it is made, and the fuel which keeps it going.

At Cambridge the prestige of physics was very high, owing to the achievements of the Cavendish Laboratory. The atmosphere was quite different from Greenwich, which is essentially a state and world institution engaged in co-operative observations of fundamental practical importance, such as the measurement of time and the determination of basic astronomical units, such as the distance of the sun. Physical discoveries were being made almost daily in the Cavendish Laboratory, and were a

general subject of conversation. Circumstances naturally inclined a Cambridge professor of astronomy to investigate the application of the new physics to the constitution of the stars.

The outbreak of the First World War in 1914 had the effect of impelling Eddington still more completely into his new line of research. As a Quaker he was a conscientious objector to military service. He concentrated on his research, and the departure of students caused him to be still less disturbed by the calls of routine lecturing, though the loss of junior members of his staff placed on him a heavy load of observational work, which he carried out and completed with his usual competence.

He began his attack on the problem of the internal constitution of the stars by attempting to explain the mechanism of the variable stars called Cepheids. These vary in brightness with extraordinary regularity. The period from maximum brightness to maximum brightness is precise for each star, usually about four days. The American astronomer Miss Henrietta Leavitt made the very remarkable discovery that the absolute magnitude or candle-power of Cepheid stars is exactly related to their period. Hence, if their period was measured, their absolute magnitude could be calculated exactly. By comparing the apparent magnitude of a Cepheid star with its absolute magnitude, it became possible to calculate its distance.

Cepheid stars have in consequence become most important milestones for measuring distances in the stellar universe. Cepheid stars have the additionally fortunate property of being particularly luminous; their candle-

power is exceptionally large. They can consequently be seen a very long distance away, and hence are particularly valuable in revealing the exact distance of very distant groups of stars. It was the discovery of Cepheid stars in the Andromeda nebula which enabled the distance of this nearest of the island universes to be determined. Harlow Shapley suggested that the periodic variation in the brightness of these stars was due to the regular expansion and contraction, like a balloon being regularly inflated and deflated.

Eddington started by trying to find the explanation of this mechanical pulsation. He thought it might arise if the material of the star behaved like the working substance of a heat engine, such as the steam in a steam engine, or if the pressure caused by the intense radiation inside the star varied in a manner which enabled it to perform mechanical work. Hitherto, a star had generally been thought of as a mass of gas whose shape was preserved by the pressure of gas inside it, like a blown-up football. Eddington's investigation led him to recognize the great importance in stars of the second kind of pressure, radiation pressure. It had long been known that a beam of light exerts a slight pressure on any object on which it falls, and the phenomenon had been invoked for explaining why comets' tails point away from the sun. It was supposed that the radiations from the sun blew the fine dust around the comet in the direction away from the sun.

Inside a star the radiations are enormously more intense than ordinary light, and consequently exert very much greater pressures. Eddington saw that the stopping-power, or opacity, of matter to these intense radiations

was of key importance, for it must be the valve which regulated the radiation-pressure inside the star. If the opacity varied in a regular way, the star might be blown up by radiation pressure when it was low, and contract again when it was high.

Thus the physics of the interaction between radiation and matter became of prime importance in trying to explain the behaviour of stars. As the intense radiations inside stars are more like X-rays than ordinary light, it became necessary to study the results of experimental physicists on their investigations of the stopping-power of matter for X-rays.

It seemed evident that radiation-pressure had a much more important role in the mechanics of stars than had hitherto been thought. Eddington laid aside the more difficult problem of explaining the pulsations of Cepheid stars, and began a fresh investigation of the simpler problem of a star in a steady state of equilibrium.

He found that if radiation-pressure, and not ordinary gas-pressure, had the chief part in bearing the upper layers of the star against their enormous gravitational weight, then it became possible to calculate the distribution of temperature and pressure inside the star by a fairly simple law.

By taking into account the effect of radiation-pressure inside the star, Eddington succeeded in bringing theory in much closer agreement with observed fact. According to previous theory, the outflow of heat from a giant star should be very great, and in fact millions of times more than is actually observed. By recognizing the opacity of the material of the star to the intense radiations inside it,

Eddington explained why the radiation observed to escape from the surface was so low.

This work of Eddington, published in 1916 and 1917, in which imagination and concrete argument were perfectly matched, showed his powers at their highest. He developed the various strands in it during the next decade, and published his results in his masterpiece: *The Internal Constitution of the Stars.*

When conscription was introduced in 1916, Eddington was exempted from military service at the University's request that he should be allowed to remain at his university post because it was in the national interest that he should do so. When the military situation became critical early in 1918, the authorities combed the country for men. Eddington was still only thirty-five, and single, so the Ministry of National Service appealed against his exemption. The tribunal before which it was heard ruled that his exemption on the ground of occupation should terminate on 1 August 1918. Eddington now applied for exemption on the ground of conscience. His application was heard before another tribunal in June 1918. In it Eddington declared:

'My objection to war is based on religious grounds. I cannot believe that God is calling me to go out and slaughter men, many of whom are animated by the same motives of patriotism and supposed religious duty that have sent my countrymen into the field. To assert that it is our religious duty to cast off the moral progress of centuries and take part in the passions and barbarity of war is to contradict my whole conception of what the

Christian religion means. Even if the abstention of conscientious objectors were to make the difference between victory and defeat, we cannot truly benefit the nation by wilful disobedience to the divine will.'

Eddington's application for exemption was supported on the ground of science by Sir Frank Dyson, the Astronomer Royal. He informed the tribunal that a grant of £1,000 had been received to send an expedition to observe the eclipse of the sun in 1919, which was of great importance, and it was hoped that Professor Eddington, with his exceptional qualifications for the task, would be available to lead it.

The Tribunal then asked why the expedition would be so important, and Eddington explained that the eclipse would take place against the background of the stars in the Hyades, that would provide an opportunity for testing Einstein's General Theory of Relativity which would be more favourable than could be expected to occur for centuries.

The Tribunal declared that they were convinced that Eddington's objection to military service was conscientious, and they expressed the opinion that his scientific work was of great importance, both to his own country and the world. They decided to grant him twelve months' exemption on the condition that he continued his scientific work, and in particular went on the expedition to test the General Theory of Relativity.

A few months later the war ended. Eddington was not required to face a tribunal again, and in due course led one of the eclipse expeditions.

Eddington did not restrict his expressions of opinion on war to his personal affairs. He published a letter in the journal *Observatory* in 1916 on *The Future of International Science*, protesting against future exclusion of German scientists from international organizations on account of their belligerent attitude during the war. He said that the patriotism of the German scientist might be wrong-headed, but was not morally debased. 'Far be it from me to deny his individual responsibility for his country's share in the evil that has befallen. The worship of force, love of empire, a narrow patriotism, and the perversion of science have brought the world to disaster. . . .' He warned that German scientists would not return to international organizations repentant. 'Nations repent of their folly, not by a sudden revulsion, but by the slow growth of a wiser outlook.'

Eddington's detachment from the war, and freedom from anti-German prejudice, helped him to perform a most valuable service to science. This was to become the first, and greatest, interpreter of Einstein's General Theory of Relativity to the Anglo-Saxon world. Einstein published his supreme achievement at the end of 1915. The Dutch astronomer de Sitter, living in the neutral country of Holland, was still in communication with London. He sent a copy of one of Einstein's papers to the Royal Astronomical Society, which Eddington received as Secretary. De Sitter sent a series of papers expounding Einstein's work, which Eddington published in the journal of the Society, starting in 1916.

With his ability, detachment and freedom from prejudice Eddington immediately appreciated the tremendous

implications of Einstein's work. He was prevailed upon against his will to explain it to his colleagues, and devoted a great deal of energy to delivering lectures and writing articles on it, which he would otherwise have devoted to his own work on the internal constitution of the stars. The imaginative, all-embracing character of the new theory, with its paradoxical results in terms of old ideas, profoundly appealed to him. He wrote a short report on it for the Physical Society, which virtually introduced the subject to British scientists.

Intense interest arose in public as well as scientific circles on the question of the truth of the new theory. As Sir Frank Dyson had originally pointed out, the forthcoming eclipse on 29 May 1919 would provide a peculiarly favourable test, for it would occur against the background of the numerous stars in the Hyades. Many of them would be near the edge of the sun's disc, and it should be possible to measure how much the rays of light arriving from these stars were bent by the sun's gravitation, as they passed near the sun. They could expect measurable displacements not in one, but in many cases, and thus diminish the chance and effect of observational error. An equally good eclipse for the purpose might well not occur again for thousands of years, for most eclipses would take place against a background of few prominent stars, or none at all.

Two expeditions were sent to observe the eclipse; one led by Eddington and Cottingham to the island of Principe in the Gulf of Guinea off West Africa, and the other, led by Crommelin and Davidson, to Sobral in Brazil. The astronomers left for their stations in an atmosphere of

world attention, and news of their observations was awaited in tense excitement. Presently the observers in Brazil telegraphed the two words 'eclipse splendid', and Eddington: 'through cloud hopeful'. On Eddington's plates good photographs of five stars were obtained, and on the Sobral plates nineteen. The places of the stars on the plates were compared with their normal places in the sky. When the displacements of the twenty-four stars were measured, they were, well within the margin of error, found to be exactly what Einstein had predicted. This was just twice as much as was to be expected according to Newtonian theory. There could no longer be any doubt that the General Theory of Relativity was substantially correct, and the greatest single advance in science since Newton had been made.

Eddington's gifts for popular exposition were now widely called upon, and greatly appreciated. Audiences flocked to hear him. He enjoyed preparing and delivering lectures for non-specialist audiences, from student societies to public meetings. His invention of apt similes and choice of appropriate quotations gave his hearers the feeling that they had at least gained some insight into what it was all about. He was the master of the fable, the paradox, the epigram, and the pun. He could compose dialogue in a natural conversational style. He had a sense of the dramatic, and devised skilful entries and exits for his scientific ideas. He had humour, and a gentle, poetic fancy.

One of the features of Eddington's lectures was that he was not a ready speaker. If his chairman was so rash as to agree to questions afterwards, Eddington often became entangled and tongue-tied in framing his answers. He

needed time to compose his thoughts, and when he was granted this, he prepared the ablest general expositions of science of his day. His *Space Time and Gravitation*, published in 1920, probably did more than any other work to give a general insight into the significance of Einstein's achievement.

Eddington became best known to the public as an expounder of relativity, and afterwards of the general philosophy of science. His own most important discoveries were not, however, in these fields, but in the internal constitution of the stars. In spite of the immense demands on him to expound Einstein's discoveries and their implications, Eddington continued to work as intensely as ever in his own field. For his own subject, the disintegration of the atom by Rutherford in 1919, and the flood of new knowledge about the structure and properties of atoms, was more significant than the General Theory of Relativity. One of Rutherford's colleagues guided him in the literature on the interaction of radiation with atoms, which was vital for his theory of the structure of the stars. In his early work in 1917 Eddington assumed that the interior of a star consisted of free atoms which had been dissociated from all chemical combinations by the high temperature. He supposed that the different kinds of atoms were mixed up together, and formed a material with an average atomic weight of about 50. The physicists pointed out to him that the new theory of the structure of the atom suggested that a different condition must exist.

The atom was a roomy structure, consisting of a nucleus with electrons revolving round it. If the atom was very hot, its electrons would fly off, and the overall size of the

atom would be much smaller. If the heat was so intense that all the electrons would fly off, then the material in the interior of the star would be a mixture of free nuclei of atoms, and free electrons. It would consist of a material made up of particles which are very much smaller than normal atoms. Two very important consequences followed. Firstly, the internal material of the stars would continue to behave as a perfect gas even at enormous pressures, which would have forced normal atoms so close together that they would no longer have behaved like a gas. Secondly, as the number of electrons in a normal atom is approximately half the atomic weight, the stellar material, whatever kind of atoms it was made of, would behave as if the average weight of its constituent particles was about 2, or twice that of the hydrogen atom.

With these two conditions, that the material of all stars is perfectly gaseous, and that the average weight of its constituent particles is 2, Eddington found it possible to calculate the temperature, density and pressure in a star of known mass and radius. He showed that if the mass of a star was known its candle-power could be calculated. He succeeded in giving a theoretical explanation of the Russell-Hertzsprung relation between the candle-po r and physical properties of stars.

His theory of stellar constitution enabled him to explain the discoveries that had been made about the faint star which is the companion of Sirius. This had been discovered by the American telescope maker Alvan Clark, who was in the habit of testing his telescopes by training them on the bright star Sirius. He was surprised to see on one occasion a small speck near Sirius, and assumed at first

that it might be due to a blemish in his telescope. Further observation proved, however, that Sirius and its faint companion were revolving round a common centre. Subsequent studies of the perturbation of Sirius by its companion showed that the faint star must be very heavy. The faintness of the star, and the quality of its light, proved that the star was very small. Calculation showed, in fact, that the Companion must be extremely dense, at least 55,000 times the density of water.

This seemed to be incredible. But Eddington pointed out that it would not be unreasonable if the star were so hot that its constituent atoms were completely bereft of all their normally revolving electrons. The star would still behave like a perfect gas, even if its density was 55,000.

He suggested that the theory of relativity would provide a test for the correctness of this conclusion about the very high density. If the Companion really were so dense, then the light emitted from it would be slowed down appreciably, owing to the enormous gravitational pull of the mass of very dense matter on it. He calculated that the light would be slowed down by about 20 kilometres a second. The astronomers at Mount Wilson Observatory in America accordingly made a very careful examination of the light from the Companion, and did indeed find a slight displacement in its spectrum, which showed that it had been slowed down by about 20 kilometres a second.

Eddington had at first supposed that the radiation inside a star exerted its pressure as if it operated like a beam of light giving a push to a solid ball-like atom. In 1921 he realized that the actual mechanism by which radiation

exerts pressure is the same as that of the photoelectric effect, the phenomenon by which television cameras work. This enabled him to develop his theory of the role of radiation-pressure inside stars. He showed that its intensity depended on the mass of the star. For a globe of material which weighed about ten million million million million million tons, the ordinary gas-pressure due to the speed of the flying particles would be enormously greater than the radiation-pressure. But in globes 1,000 times heavier the radiation-pressure would greatly exceed the gas-pressure. Eddington said that in globes within these two limits 'we may expect something interesting to happen. What "happens" is the stars'.

The masses of the vast majority of stars do in fact fall within these limits. It appeared, then, that matter is drawn together by gravitation to form stars. As they are made more and more compact by gravitation, their internal temperature rises, in the same manner as the air in a closed bicycle pump is raised by pressure. As the temperature rises, the radiation pressure increases, until a point comes where the radiation-pressure bursts the star apart. We are led 'to think that radiation pressure is the agent which has cloven chaos into stars'.

Astronomers had long known that the contraction of matter under the force of gravitation could raise it to a high temperature, but could not keep it at such a temperature for an astronomically long period. Stars must therefore be drawing on some other source of energy, which enabled them, like the sun, to pour out vast quantities of energy for millions of years without any apparent diminution. They suspected that this energy must some-

how come from within the atom, and the discovery of radioactivity made this seem very probable.

Little insight into how it actually took place was gained until 1919, when the atom was first successfully disintegrated. Henry Norris Russell made a suggestive review of the condition which a sub-atomic source of energy must satisfy, if it were to be a fuel for stars. Then, in 1920, Eddington's colleague at Cambridge, F. W. Aston, showed that the mass of a helium atom, which was presumably an atomic combination of four hydrogen atoms, was less than the total mass of four separate hydrogen atoms. It was concluded that this disappearance of mass was due to the emission of sub-atomic energy when the helium atom had been originally formed in the processes of nature out of hydrogen, for, as Einstein had shown long before, according to the theory of relativity, mass and energy are equivalent.

Later in 1920, the French scientist Perrin, and Eddington, both suggested that the process which provided the energy that kept the stars shining was the synthesis of helium out of hydrogen, which was going on under the intense conditions in their interiors.

The first plausible theory of how this synthesis takes place was suggested by Bethe in 1938. He showed how it might occur through the intermediation of atoms of carbon.

The realization that the synthesis of helium might be the chief source of stellar energy emphasized the fundamental importance of hydrogen as both the basic material and the basic fuel of the universe. Eddington, and the Danish astronomer Strømgren, simultaneously calculated the abundance of hydrogen in the stars, and showed that

it formed by far the largest part of all the matter in the universe.

The overwhelming abundance of hydrogen in the universe has been one of the foundations of the new theories of the stars which have been elaborated by the younger astronomers of the present generation, who have advanced beyond Eddington, by developing ideas and methods to which he contributed so much.

Eddington devoted his last years to trying to work out a comprehensive mathematical theory of the whole universe, comprehending the depths of space and the behaviour of the atom. His results have not commanded much acceptance, though his aim is one which will always appeal to profound scientists. His younger successors, though sympathizing with his aim, are inclined to think that he depended too much on the physical ideas which have already been discovered. They believe that many more new fundamental ideas must be discovered before it will be possible to carry out such a comprehensive description of physical nature as Eddington attempted.

Eddington published 157 scientific papers and thirteen books. His *Internal Constitution of the Stars* was the most original and creative. His books of exposition on *Stars and Atoms* and on *The Expanding Universe* had a large sale in many languages. His Gifford Lectures on the philosophy of science, published under the title of *The Nature of the Physical World*, were translated into nine languages, and provided the medium through which a wide public acquired its notions of modern scientific discoveries and ideas.

He received very many honours. Besides being elected

a fellow of the Royal Society at an early age, he was awarded one of its Royal medals. He received the Gold Medal of the Royal Astronomical Society, and served it as President and Secretary. He was knighted and he received the Order of Merit. He received twelve honorary degrees, and was elected a foreign member of many academies, including the Academy of Sciences of the U.S.S.R. His prizes and medals included awards from the French Academy of Sciences, and the National Academy of Sciences of the United States.

Eddington's health appeared to decline rather suddenly. It gave concern during the last year of his life. He suffered considerable pain, but he did not tell anyone about it. Even his most intimate friend did not know that he had more than a passing indisposition. By November 1944 it became evident that he would have to have an operation. He went on working on his treatise on fundamental theory, which was already in its sixth draft, and laid down his pen only at the end of his night's work, before leaving for the hospital on the following morning. The operation showed that he was suffering from an incurable cancer. He lived on for another fortnight, and then, on 22 November he died.

Eddington was buried beside the grave of his mother in St. Giles' Cemetery, which is just behind the Observatory at Cambridge, and contains the remains of John Couch Adams, and other Cambridge astronomers.

He bequeathed many of his papers to the Royal Astronomical Society, and his considerable fortune in trust to Trinity College, which was received after the death of his sister in.

Many heartfelt appreciations of Eddington were expressed. Henry Norris Russell described him as 'a master in many fields, but most of all in astrophysics. He was distinguished by a remarkable physical insight. . . . He contributed greatly to the cause of international co-operation in science, not only by his participation in congresses and meetings, great and small, but by his quiet, cordial relations with those who . . . appreciated him equally as host and guest'. With his death, astronomers felt that they had 'lost a friend'.

REFERENCES

The Life of Arthur Stanley Eddington, by A. Vibert Douglas. Nelson.

British Scientists of the Twentieth Century, by J. G. Crowther. Routledge and Kegan Paul.